CALIFORNIA HYDROGEN FUELING STATION GUIDELINES

CONSULTANT REPORT

CALIFORNIA ENERGY COMMISSION

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Technical Report

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PREFACE

This report was prepared by TIAX LLC for the California Energy Commission as part of Contract 600-01-095, "Hydrogen Fueling Infrastructure Study." It is a deliverable required under Task 3, "Development of a Hydrogen Fueling Station Report." TIAX and its subcontractors St. Croix Research, the University of California at Davis Institute of Transportation Studies, USA PRO & Associates, SunLine Services Group, and SDV-SCC prepared this report. Sandra Fromm and Bill Blackburn were the Energy Commission Project Managers.

Two "California Hydrogen Fueling Station Guidelines" Task 3 reports exist. This is the full report, which includes technical details (e.g., pertaining to the different types of hydrogen fueling stations) and individual profiles of existing hydrogen fueling stations in California. The other report is the Executive Summary Task 3, which has less technical details and specific station descriptions and is bound separately.

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1. INTRODUCTION

1.1 Objective and Scope

This document is intended to be a resource for anyone considering the installation of a hydrogen fueling station. Its objective is to provide guidance for planning, designing, siting, permitting, and procuring facilities to refuel hydrogen-fueled vehicles.

The following considerations guided the scope of this document:

- This report seeks to balance the needs of those who are committed to a hydrogen fueling station and have to assess equipment options, those who are considering a hydrogen fueling station and need planning guidelines, and those who are interested in general hydrogen fueling station background information.

- These guidelines are intended to apply to fuel cell vehicles and hydrogen-fueled vehicles with internal combustion engines.

- This document is aimed at California hydrogen vehicles and fueling stations, but most of the information is independent of geographic location.

- This document is intended to be applicable for a spectrum of applications ranging from refueling a small number of light-duty hydrogen vehicles to large fleets of heavy-duty hydrogen vehicles (e.g., transit fleets required by the California Air Resources Board to deploy fuel cell buses).

- These guidelines apply to vehicles that are directly fueled with hydrogen. While vehicles with on-board reformers (which may be fueled with methanol, natural gas, gasoline, or other hydrocarbons) are being developed and tested, they are not yet as commonly available as direct-hydrogen-fueled vehicles.

- These guidelines focus on refueling vehicles that store hydrogen as a compressed gas or cryogenic liquid. Impressive progress is being made with respect to on-vehicle hydrogen storage using metal hydrides, carbon nanostructures, chemical solutions, and other innovative technologies; however, because these are not as commonly available as compressed and liquid hydrogen storage at this time, their particular fueling station requirements are not addressed in this document.

- An objective of these guidelines is to help planners to carry out tradeoff analyses and make prudent choices appropriate to their specific requirements; however, this document does not include quantitative cost data for fueling station design services, equipment items, and installation work.

- These guidelines are intended to be objective and unbiased; however, technology discussions and guidelines are based on available information. Technologies are changing rapidly, and hydrogen fueling station planners should seek current performance information and commitments directly from contractors and equipment suppliers prior to making firm decisions.

- This document emphasizes near-term practical engineering information. A wealth of literature is available pertaining to the long-term benefits of a hydrogen economy and the scientific principles associated with fuel cells and other hydrogen equipment.

1.2   Report Organization

The various subjects pertaining to hydrogen fueling stations are laid out here in an order intended to provide the most utility and clarity for typical planners: Section 2 describes hydrogen fueling station technology options, including the basic station types and their associated requirements and tradeoffs, the principal equipment items involved, and same sizing guidelines. Section 3 addresses hydrogen fueling station permitting (including potentially applicable codes and standards), procurement and contracting, installation, training, and related subjects. Appendix A includes detailed profiles of five existing hydrogen fueling stations in California. These are selected to illustrate the breadth of current size and technology options, and they include quantitative specifications where they are available. A separately bound Executive Summary of this report is available for readers seeking an overview without technical details.

Subsection 1.3 provides a summary of information items that must or should be known before planning a specific hydrogen fueling station design and procurement. A tabulation of these items is included, which references subsequent report sections where each item is discussed in more detail.

1.3   Summary of Needed Information

Table 1-1 lists some of the general information items that a fleet manager or prospective hydrogen fueling station project developer should know before proceeding with specific planning. The items labeled "necessary" are needed at the very beginning. The items labeled "helpful" will be needed at an early stage, but they are not absolutely necessary to begin initial planning. The last column in the table shows where each information item is discussed in more detail in this document. Table 1-1 is intended to serve as a checklist for the information needed to start planning a hydrogen fueling station, and it also serves as a guide regarding which topics are addressed in which sections of this report.

Table 1-1.   Information needed to initiate planning of a hydrogen fueling station.

Information Item	Necessity and Reason	Discussed Further in Report Section(s)
Vehicles to be fueled with compressed or liquid hydrogen?	Necessary — Substantially affects station process and dispenser requirements	2.1.1
Number of vehicles to be refueled, typical miles driven per day, and estimated fuel consumption?	Necessary — Needed to size station	2.2.1, 2.2.2, 2.2.3
Vehicle refueling window and flexibility?	Necessary — If, for example, all vehicles must be refueled each day within a narrow time period, this affects the station equipment requirements	2.2.4
Fueling station objective?	Necessary — Is the station objective just to refuel vehicles or to support technical R&D? This affects the station type tradeoffs and the final design	2.1.1, 2.1.2
Station to be private or public access?	Necessary — Public-access fueling stations have additional requirements	2.1.2, 3.1.3
Fueling station permanence?	Necessary — Mobile or skid-mounted stations can provide temporary refueling capability, but permanent installations usually have lower long-term life-cycle costs	2.1.2, 2.3.2.5
Compressed hydrogen vehicle storage pressure, receptacle type, and data link?	Necessary — This information must be known so that the dispenser will be compatible with the vehicle	2.1.1, 2.3.1
Liquid hydrogen vehicle saturation pressure range, receptacle type, and vapor-management system?	Necessary — This information must be known so that the dispenser will be compatible with the vehicle	2.1.1, 2.3.2.6
General station site area and characteristics?	Necessary — To ensure that station will comply with codes and be compatible with other structures, neighborhood (industrial or residential), and vehicle access	2.3.2, 3.1, 3.2
Utilities available at site?	Necessary — Available electric and natural gas service can affect station type options and tradeoffs	2.3.2, 3.1, 3.2
Hydrogen vehicle fleet size, growth projection?	Helpful — To size station to accommodate future growth	2.2
Funding sources and status?	Helpful — Funds from some sources carry contracting and/or schedule restrictions	2.1.2, 3.3
Availability of truck-delivered hydrogen	Helpful — Nearness to a hydrogen plant and costs of truck-delivered compressed or liquid hydrogen affects station type tradeoffs	2.1.2, 2.3.2.2, 2.3.2.6

Table 1-1.   Information needed to initiate planning of a hydrogen fueling station (concluded).

Information Item	Necessity and Reason	Discussed Further in Report Section(s)
Station to be integrated with other facilities?	Helpful — Affects station design	2.3.2, 3.2
Local permitting authority's experience and attitude regarding hydrogen?	Helpful — Early identification of and communications with permitting authorities helps to avoid delays and surprises	3.1.3
Understanding of codes and standards that permitting authorities will apply	Helpful — Because no authority-adopted codes are specific to hydrogen fueling stations, different authorities can have different interpretations of requirements that affect the station design	3.1.1, 3.1.2, 3.1.3

2. HYDROGEN STATION TYPES, SIZES, AND DESIGN OPTIONS

Section 2.1 establishes some basics such as the difference between compressed and liquid hydrogen fueling, and it also summarizes current hydrogen fueling infrastructure options. Section 2.2 provides some guidelines for considering the number of hydrogen vehicles, their fuel consumption, refueling windows, and other factors in order to size hydrogen fueling stations and identify suitable technologies. Section 2.3 then describes specific hydrogen fueling station technologies in terms of the key components and integrated designs.

2.1 Basic Hydrogen Fueling Infrastructure Options

2.1.1 Types of Hydrogen-Fueled Vehicles and Hydrogen Properties

This section establishes some basics regarding hydrogen properties including some important differences between compressed and liquid hydrogen that affect both vehicle and fueling station designs and performance. Table 2-1 summarizes some key physical and chemical properties of hydrogen. Most of hydrogen's unique properties derive from the low molecular weight, small size, and simplicity of the H_2 molecule. Many references (e.g., References 1, 2, and 3) discuss hydrogen properties in detail. The purpose of Table 2-1 is to provide a convenient point-of-reference for subsequent discussion of topics such as hydrogen storage and safety.

Relative to other candidate transportation fuels, hydrogen has the highest heating value on a mass basis (e.g., Btu/Lbm or kJ/kg) but the lowest heating value on a volume basis (e.g., Btu/ft^3 or kJ/m^3). This is because hydrogen's mass density, which scales approximately with molecular weight, is extremely low. A key challenge to using hydrogen as an automotive fuel is how to store it on the vehicle and also at the fueling station. Hydrogen storage as a highly compressed gas or cryogenic liquid are the two most highly developed storage modes at this time. Compressed hydrogen is used somewhat more commonly on vehicles than liquid hydrogen storage. As mentioned in Section 1.1 and detailed in many references, hydrogen adsorption (e.g., in carbon materials) and absorption (e.g., in simple metal hydrides) are being researched and some of these storage technologies are progressing toward commercialization.

Table 2-1. Key hydrogen physical and chemical properties.

Hydrogen Property	Metric Units	U.S. Customary Units
H_2 molecular weight	2.0016	2.0016
Lower heating valve (LHV)	120,020 kJ/kg	51,600 Btu/Lbm
Density at NPT	0.080 kg/m^3	0.0050 Lbm/ft^3
LHV x density at NPT	9,600 kJ/m^3	258 Btu/ft^3
Saturation Temp. at 1 atm	-253°C	-423°F
Critical temperature	-240°C	-400°F
Critical pressure	1.29 MPa	187 psia
Heat of vaporization in air	446 kJ/kg	192 Btu/Lbm
Flame temperature in air	2,045°C	3,713°F
Stoichiometric combustion in air	29.5% Vol	29.5% Vol
Flammability limits in air	4.1-75% Vol	4.1-75% Vol
Minimum ignition energy	2×10^{-5} J	1.9×10^{-8} Btu
Burning velocity in NPT air	2.7-3.3 m/s	8.7-16.7 ft/s
Diffusion coefficient in NPT air	0.61 cm^2/s	6.6×10^{-4} ft^2/s
Vapor density, MW ratio to air	0.07	0.07
Flame visibility in sunlight	none	none
Odor, color, taste	none	none

Figure 2-1 shows the mass density of compressed and liquid hydrogen at conditions representative of vehicle and fueling station applications. The density is shown in the mixed-system units of kg/gallon because this makes it approximately equal to the ratio of hydrogen-to-gasoline energy (in terms of lower heating value, LHV) in the same volume.[1] Factors are shown on the graph for converting to kg/m^3 or Lbm/ft^3.

Figure 2-1 shows the compressed hydrogen curve for hydrogen at 60°F and pressures from 3,600 to 5,000 psig. These are the most common compressed hydrogen storage pressures used at this time. Research is underway to develop technology to cost-effectively store hydrogen at pressures up to 10,000 psig, but storage above 5,000 psi is not yet in common use. Compressed hydrogen storage pressures involve subtle tradeoffs and the optimum pressure depends on the specific application. Obviously, the gas density increases as the pressure increases; however, this increase is not nearly linear due to non-ideal gas effects. Also, higher pressures require thicker or otherwise-stronger vessels, higher compression energy investment, more challenging heat-of-compression compensation issues, and possible code-compliance concerns.

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[1] The volume-LHV of gasoline is roughly 122,000 kJ/gallon (depending on the blend), and the LHV of hydrogen is 120,020 kJ/kg.

0.4

* These units are roughly equal to the hydrogen-to-gasoline energy-density ratio.
Multiply by: 264 for kg/m^3, or 16.5 for Lbm/ft^3

0.35

0.3

Atmospheric pressure (-423°F)

0.25

Density (kg / gallon*)

Saturated Liquid Hydrogen

0.2

0.15

Compressed Hydrogen at 60°F

172-psig critical point (-400°F)

0.1

5,000 psi

0.05

3,600 psi

0

0   500   1,000 1,500 2,000 2,500 3,000 3,500 4,000 4,500 5,000

Pressure (psig)
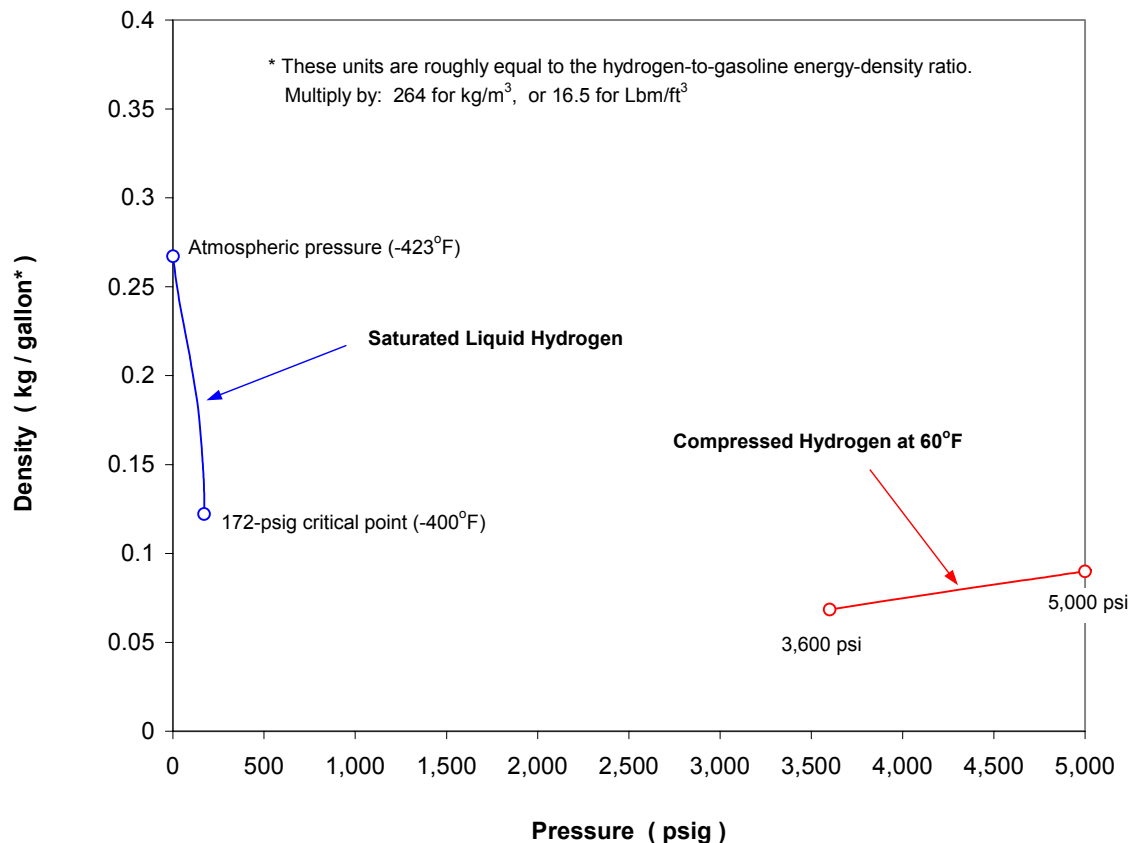
Figure 2-1. Mass density of compressed and liquid hydrogen at conditions applicable to hydrogen vehicles and fueling stations

The liquid hydrogen curve in Figure 2-1 corresponds to a saturation liquid (i.e., in equilibrium with its vapor, which is the way liquid hydrogen is usually stored) for atmospheric pressure to the critical pressure. Figure 2-1 shows that (like most fluids) liquid hydrogen's density decreases as its saturation pressure increases, which can sometimes appear to be counter-intuitive. As will be discussed subsequently, liquid hydrogen is usually transported in cryogenic tank trucks at 10 to 20 psig, and it is stored in station tanks at pressures up to approximately 150 psig. Its temperature is less than -400°F at these conditions, and highly insulated vessels (to be discussed in Section 2.3.2.2) are required to minimize heat transfer and the resultant boil off.

Figure 2-1 shows that the density of liquid hydrogen (which is in the approximate range 0.15 to 0.25 kg/gallon) is at least two to three times the density of hydrogen at 3,600 psig (approximately 0.07 kg/gallon) and 5,000 psi (approximately 0.09 kg/gallon); however, the choice of compressed or liquid storage modes on vehicles or at fueling stations involves many technical tradeoffs, most of which will be discussed in subsequent sections. As will be discussed in Section 2.3.2.2, some hydrogen fueling station designs include hydrogen stored in both liquid and compressed forms.

A particular caution should be noted with respect to calculating hydrogen properties. Hydrogen exists in two molecular forms called orthohydrogen and parahydrogen. The relative concentrations of the two forms depend on the state (e.g., temperature) of the hydrogen, and this can affect certain properties (e.g., enthalpy). It is important to ensure that the properties applicable to the appropriate hydrogen state are used for certain calculations. Additional discussion of orthohydrogen and parahydrogen is beyond the scope of this guidebook (e.g., see Reference 4).

2.1.2 Hydrogen Supply or Production Options

Hydrogen can either be delivered to or produced at the fueling station. It can be delivered as a trucked compressed gas, a trucked cryogenic liquid, or (in rare cases) through a hydrogen pipeline. Either electrolysis of water or reforming of hydrocarbons such as natural gas can produce hydrogen at the fueling station. Each of these delivery and production modes requires a significantly different fueling station design. While hydrogen dispensers are basically the same regardless of the delivery or production mode, dispensers for compressed and liquid hydrogen fueled vehicles are completely different. These combinations of hydrogen delivery or production at the station, compressed or liquid hydrogen dispensing, and various components and integration alternatives make up the array of hydrogen fueling station design options.

Figure 2-2 illustrates the basic hydrogen delivery or production modes and some of the fueling station configuration options that are appropriate to each mode. These can be regarded as seven basic hydrogen fueling infrastructure options. These options are introduced and briefly discussed to provide a foundation for subsequent consideration of station sizing and tradeoff analyses and to determine the most suitable type of station for a given set of circumstances. Sections 2.2 and 2.3 provide details regarding station components and integrated fueling station designs.

The options illustrated in Figure 2-2 are shown with only compressed hydrogen dispensing. Variations on the delivery modes and station designs depicted in Figure 2-10C and D are suitable for dispensing liquid hydrogen, and these will be discussed in Section 2.3.2.6.

Figure 2-2 illustrates the following summary explanations of the hydrogen supply or production and fueling station. Section 2.3 provides technical details.

Mobile Fueling Stations

Compressed hydrogen delivery can provide a mobile fueling station capability (Figure 2-2A) if the trailer or truck with the compressed hydrogen vessels is also equipped with dispensing equipment. Small trailer-mounted electrolyzers, compressors, and dispensers can also provide a mobile fueling capability. Various companies have announced the availability of mobile hydrogen fuelers. A mobile hydrogen fueling station may be the only option for supporting traveling hydrogen vehicle demonstrations,

A.

MOBILE STATION WITH HP GAS
STORAGE, OPTIONAL COMPRESSOR,
AND DISPENSING EQUIPMENT
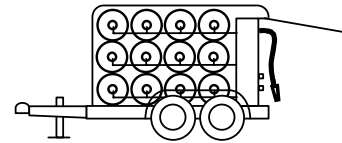
B.
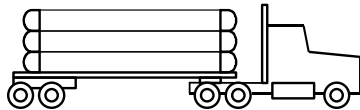
TRUCK DELIVERY (E.G., FROM
NG REFORMER AND
COMPRESSION PLANT)
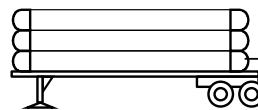
COMPRESSED
HYDROGEN TUBE
TRAILER
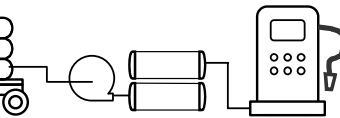
OPTIONAL
COMPRESSOR &
HP GAS STORAGE

DISPENSER

C.
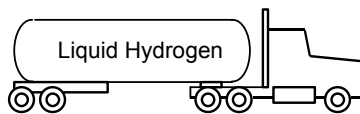
Liquid Hydrogen

TRUCK DELIVERY (E.G., FROM NG
REFORMER AND LIQUEFACTION PLANT)
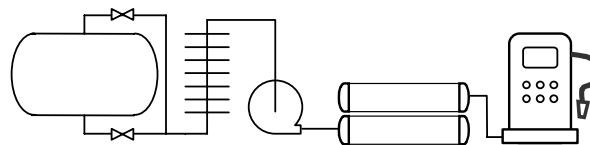
LIQUID HYDROGEN STORAGE, VAPORIZATION,
COMPRESSION, HP GAS STORAGE

DISPENSER

D.
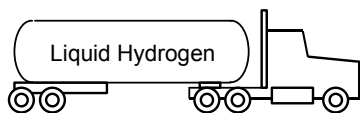
Liquid Hydrogen

TRUCK DELIVERY (E.G., FROM NG
REFORMER AND LIQUEFACTION PLANT)
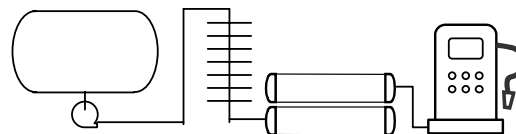
LIQUID HYDROGEN STORAGE, PUMPING,
VAPORIZATION, HP GAS STORAGE

DISPENSER

Figure 2-2. Simplified illustration of hydrogen supply and production modes including fueling station configuration options (continued on next page)
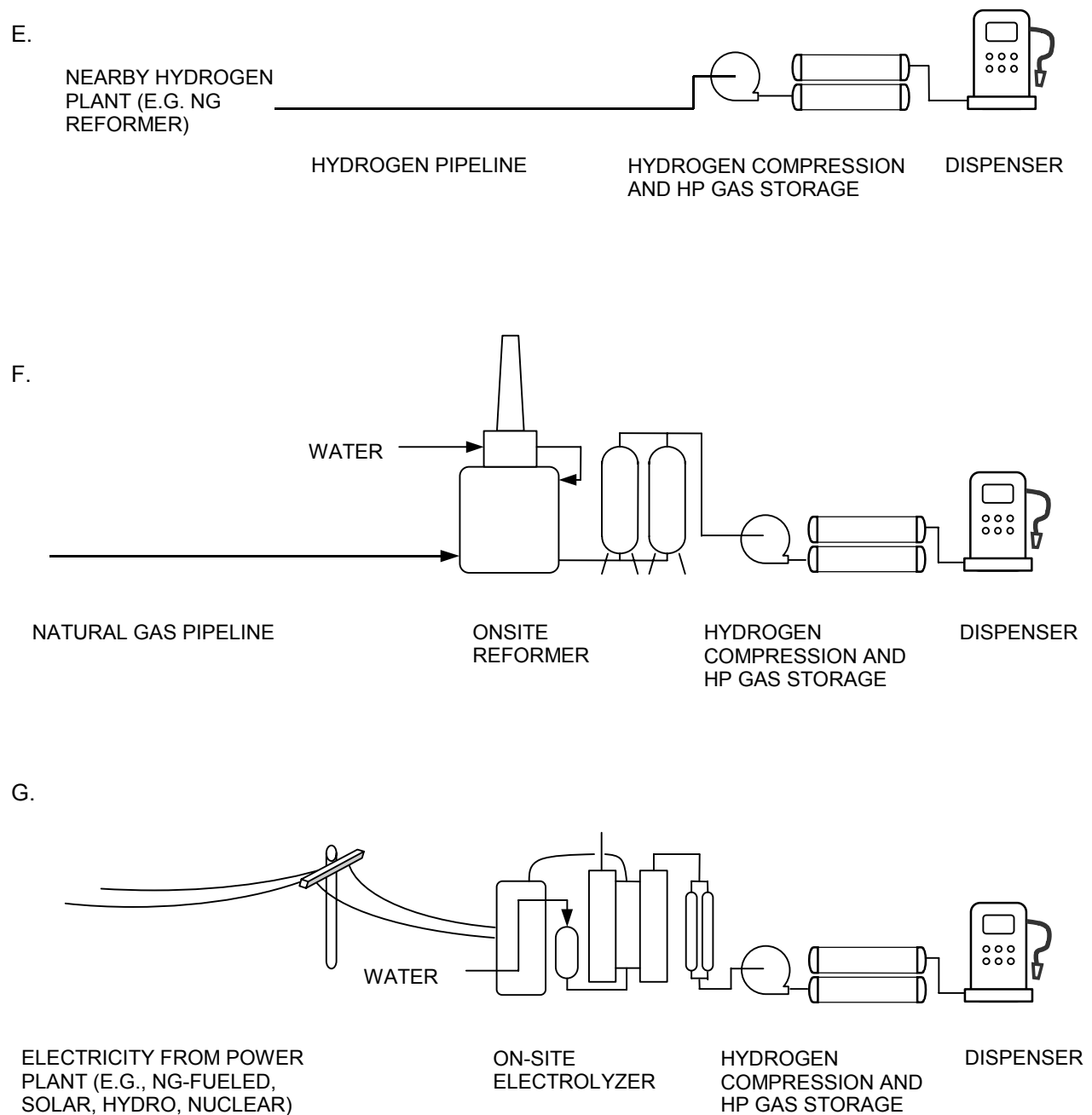
E.

NEARBY HYDROGEN
PLANT (E.G. NG
REFORMER)

HYDROGEN PIPELINE

HYDROGEN COMPRESSION
AND HP GAS STORAGE

DISPENSER

F.

WATER

NATURAL GAS PIPELINE

ONSITE
REFORMER

HYDROGEN
COMPRESSION AND
HP GAS STORAGE

DISPENSER

G.

WATER

ELECTRICITY FROM POWER
PLANT (E.G., NG-FUELED,
SOLAR, HYDRO, NUCLEAR)

ON-SITE
ELECTROLYZER

HYDROGEN
COMPRESSION AND
HP GAS STORAGE

DISPENSER

**Figure 2-2. Simplified illustration of hydrogen supply and production modes
including fueling station configuration options (concluded)**

and it may be suitable for low-volume temporary stationary applications. Permitting of mobile fuelers, especially when parked and used in a stationary mode, has received diverse interpretations by different local authorities. No mobile liquid hydrogen fueling stations (that include both hydrogen storage and dispensing) are known to exist, although they are probably feasible (e.g., liquid natural gas mobile fueling stations exist). Section 2.3.2.5 provides details regarding mobile hydrogen fueling station technologies, configuration options, and suppliers.

Compressed Hydrogen Tube Trailer Delivery

Compressed hydrogen delivered to a fueling station can supply hydrogen for dispensing. Small-volume portable pressure vessels (referred to as K bottles) or larger-capacity tube trailers can be connected directly to the dispenser, and more of the hydrogen can be transferred to the vehicle fuel tanks if they are connected in a sequenced-cascade fashion (see Section 2.3.2.1). Figure 2-2B illustrates how almost all the hydrogen in the tube trailer can be transferred to the vehicles if they are connected to a compressor and gas storage vessels. The permitting of parked tube trailers connected to stationary equipment is also subject to various interpretations by local authorities. Section 2.3.2.1 provides technical details including configuration options for using tube trailers or K bottles to supply hydrogen for compressed hydrogen fueling stations.

Liquid Hydrogen Delivery

Liquid hydrogen can be delivered to the fueling station via cryogenic tank truck, which transfers the liquid to the station tank. Because of its much higher density (as discussed in Section 2.1.1), considerably more hydrogen is transported as a cryogenic liquid in tank trucks than as a compressed gas in tube trailers. The delivered liquid is maintained at temperatures below -400°F in one or more vacuum-jacketed vessels at the station. This liquid can be vaporized and warmed (and/or the boil-off vapor can be warmed) in a heat exchanger and then compressed into high-pressure gas storage vessels that supply the dispensers (as sketched in Figure 2-2C). Alternatively, for stations with higher throughputs, the liquid can be pumped to a high pressure and then vaporized (as sketched in Figure 2-2D). This saves costs by eliminating the multi-stage compressor and its substantial drive power requirements. Delivered liquid hydrogen is the most suitable supply mode for stations that dispense liquid hydrogen. Stations with liquid hydrogen delivery/storage and liquid hydrogen dispensing are conceptually simple. Pumped transfer or pumpless pressure transfer can be employed, depending on factors such as the relative saturation pressures in the station and vehicle tanks. Section 2.3.2.2 contains specific technical information regarding stations that receive and store liquid hydrogen.

Hydrogen Pipeline Delivery

Figure 2-2E sketches how, in principle, hydrogen can be delivered to the station through a hydrogen pipeline and compressed, stored, and dispensed; however, there are few hydrogen pipeline networks in the United States and the only ones in California are local to a few petroleum refineries and industrial process plants. Therefore, except in a few locations, this type of station is not an option at this time and is not addressed in detail in this document.

On-Site Hydrogen Production by Hydrocarbon Reforming

Reformers are devices that produce hydrogen by reacting hydrocarbons with steam. The initial reaction products are principally hydrogen plus carbon monoxide, which is sometimes combined with more water in a shift reactor to produce hydrogen plus carbon dioxide. Natural gas is the most commonly used feedstock, although reformers can be designed to process almost any hydrocarbon. Most of the hydrogen produced in the United States comes from natural gas reformer plants that are too large for one fueling station; however, progress is being made to perfect cost-effective small-scale reformers and some of these are being used or tested at existing hydrogen fueling stations. Section 2.3.2.3 describes the reformer technologies being developed for station applications - steam reforming, auto-thermal reforming, and partial oxidation. Aside from the reformer itself, other equipment including water purifiers, fuel burners, shift reactors, and hydrogen purifiers may be required, depending on the specific reformer technology. Figure 2-2F illustrates how a gas compressor, high-pressure vessels, and dispenser are also needed to use a reformer at a fueling station. On-site reformers may be an attractive option for compressed hydrogen stations with a high throughput, access to inexpensive natural gas, and suitable site conditions. Section 2.3.2.3 provides additional details.

On-Site Hydrogen Production by Electrolysis

In principle, an electrolyzer is basically a fuel cell operating in reverse — electricity is consumed to produce hydrogen and oxygen from water. Electrolysis has been used for many years to produce hydrogen for various industrial applications, but the total production by electrolysis is much less than the production by natural gas reforming. A key parameter for electrolyzers is the ratio of hydrogen production to electric power consumption. Electrolyzers are available in the relatively small sizes needed for hydrogen fueling stations. Section 2.3.2.4 describes electrolyzer technologies, including proton exchange membranes and alkaline electrolyzers. Aside from the electrolyzer cell itself, equipment for power conditioning, water purification, and hydrogen clean up is needed (although some manufacturers package all this equipment as an integrated unit). There is substantial interest in hydrogen production by electrolysis because this is the one infrastructure scenario that has the potential of being completely renewable and pollution-free (i.e., if the electric power is produced by solar, wind, or similar means). A number of existing hydrogen fueling stations produce hydrogen on-site through

electrolysis, and some use solar energy to generate part of the electric power. As with reformers, a compressor, storage vessel, and dispenser are also needed at a compressed hydrogen fueling station (as sketched in Figure 2-2G). Section 2.3.2.4 contains more information regarding on-site electrolyzer stations.

2.2 Hydrogen Fueling Station Capacity, Type, and Size Planning

Important steps in planning a hydrogen fueling station include estimating the needed dispensing capacity, determining which types of stations are suited to that capacity, considering growth requirements, and sizing key station components. Sections 2.2.1 through 2.2.4 discuss guidelines for these planning steps.

2.2.1 Station Dispensing Capacity

Dispensing capacity is a critical requirement affecting the fueling station design. This capacity is the maximum quantity of hydrogen fuel capable of being transferred to vehicles over some period of time during normal expected fueling operations. The capacity depends on a wide variety of parameters including station components, vehicle characteristics, and fueling procedures.

The number and type of vehicles refueling at the station are important design considerations for station sizing, but the expected refueling procedure can have significant effects on station design and capacity as well. A station designed to refuel a given number of vehicles in rapid succession may be quite different than a station designed to randomly refuel the same number of vehicles throughout the day. The desired fueling time per vehicle can also have a significant effect on station capacity. Section 2.2.1.1 discusses vehicle and fleet characteristics, and Section 2.2.1.2 considers other factors that affect station capacity requirements.

2.2.1.1 Vehicle and Fleet Characteristics

The number of vehicles that will refuel at a station, vehicle driving patterns, and vehicle fuel economies will determine the quantity of hydrogen to be dispensed. The station design must satisfy the demand. For fleet stations, the number of vehicles will generally be known or determinable. For stations serving vehicles that may refuel at a variety of sites, the number of vehicles refueling per day may vary. The average number of vehicles refueling at the station must then be estimated.
The vehicle driving patterns determine how many miles vehicles drive per day. In some cases, the mileage may be well known (i.e., in transit bus fleets). In other cases, vehicle mileage may vary significantly from day to day. For this situation, the average vehicle mileage must be estimated for the vehicles refueling at the station. In general, estimates

should be conservative (overestimates); otherwise, the station design may not provide the necessary capacity.

Fuel economies can vary widely from vehicle to vehicle. Since fuel cell vehicles utilize new technologies, their fuel economies are not well known and can be expected to change over time as vehicle designs improve. Once again, station planners should conservatively estimate average fuel economy for the vehicles refueling at their stations.

Fueling station planners should determine their vehicle fuel economy and driving patterns based on the vehicles expected to refuel at the station. Ballpark estimates are given here to assist in estimating fuel usage if little information is available. Near-term light-duty fuel cell vehicles are assumed to have a fuel economy of roughly 0.02 kg/mile for hydrogen. If the vehicle is driven 12,000 miles per year, the average daily hydrogen fuel use will be 0.66 kg/day. Near-term fuel cell transit buses are assumed to have a fuel economy of roughly 0.14 kg/mile for hydrogen. Fuel cell buses may initially be dispatched on somewhat shorter-than-average routes that average 40,000 miles/year. The resulting average daily hydrogen fuel use would be 15.7 kg/day. Table 2-2 summarizes these numbers and the fuel use in kilograms per day and standard cubic feet per day.

Table 2-2. Hydrogen fuel cell vehicle representative fuel usage

Vehicle Type	Fuel Consumption		Miles/Year	Average Daily Usage (kg/day)	Average Daily Usage (scf/day)
	kg/mile	mile/kg			
Light Duty	0.02	50	12,000	0.66	280
Transit Bus	0.14	7	40,000	15.7	6,630

The average fuel usage per day is the product of the number of vehicles, the average daily mileage, and the average vehicle fuel consumption. The average fuel usage per day may not be the peak fuel usage per day. The weekday variation for transit buses is expected to be relatively small because transit routes are fixed, thereby constraining daily mileage, and buses generally refuel once a day. For light-duty fleets and station sharing vehicles, daily mileage varies and vehicles are less likely to refuel once a day. The worst-case scenario for these stations is to have all vehicles refuel on the same day and then have several days without any vehicles refueling. While this scenario is unlikely, station planners should consider reasons why vehicle refueling might not be regular. In addition, the estimated average daily fuel usage should be increased by a safety factor to ensure conservative sizing.

2.2.1.2 Other Factors Affecting Station Capacity

There are other important refueling characteristics that affect station capacity requirements. The station must be designed to deliver the peak anticipated fuel usage.

The expected station-fueling pattern must be understood to properly size the station. The fueling pattern may be random, regular, or constant. During random refueling, vehicles refuel as needed without a definite pattern. Regular refueling refers to a predictable pattern of refueling. During constant refueling, vehicles refuel one after another at a set time. Transit agencies generally use constant refueling where most buses line up and refuel continuously at a set time each day (typically in the evening). Conventional light-duty vehicle stations usually exhibit random refueling.
Stations exhibiting truly random refueling can use the estimate of average daily fuel usage in station sizing. Stations exhibiting constant refueling must add further considerations in order to properly size the station. A station designed to produce and deliver a certain volume of hydrogen over a 24-hour period may not be able to dispense the same volume over a shorter period. If all vehicles refuel during a shorter interval than 24 hours, for example a 4-hour interval of constant refueling, then the station must dispense the full average daily volume of hydrogen over the shorter interval.
Section 2.2.4 will discuss these issues in more detail.

Additional factors that affect hydrogen fueling station capacity planning include growth prospects and budget considerations. Planners should consider possible future hydrogen vehicle growth because stations can be designed to accommodate increased capacity requirements with relatively economical modifications (see Section 2.2.3). Budget constraints can affect the conservatism with which projected dispensing capacity requirements can be met with a specific design. Budgets can also constrain optimal station designs, e.g., operations that would prefer filling vehicles quickly with a large compressor or cascade may be required to use smaller components that fill vehicles over longer time periods.

Budgets and funding sources sometimes also affect tradeoffs between station capital and operating costs. For example, initial funding availability sometimes forces planners to choose options with lower initial costs but higher life-cycle costs. The best-suited hydrogen fueling station design within given budget constraints will result from careful analysis of current and future hydrogen fueling requirements and prudent planning with respect to the fueling station design options for meeting those requirements.

2.2.2 Station Type Suitability

Alternative hydrogen fueling station designs were illustrated in Figure 2-2 and briefly discussed in Section 2.1.2. Section 2.3 provides more details regarding these designs. A basic option that substantially affects the station design is whether the hydrogen will be produced at the station (e.g., by a reformer or electrolyzer) or produced at a central plant and delivered to the station (e.g., as a compressed gas or cryogenic liquid).

Different station designs and hydrogen delivery or production options are suitable for different dispensing capacity requirements; however, many other factors, such as proximity to central hydrogen plants, station site conditions, capital vs. operating cost tradeoffs, and site conditions also affect hydrogen fueling station design suitability.

Moreover, there is very substantial overlap with respect to which station types are appropriate for a given hydrogen-dispensing requirement.

Figure 2-3 shows the approximate ranges of daily hydrogen usage for which each type of fueling station is suited. This graph was constructed by the authors of this report by considering the basic tradeoffs involved and reviewing similar projections by equipment and design companies such as Praxair (Reference 5) and APCI (Reference 6). There is
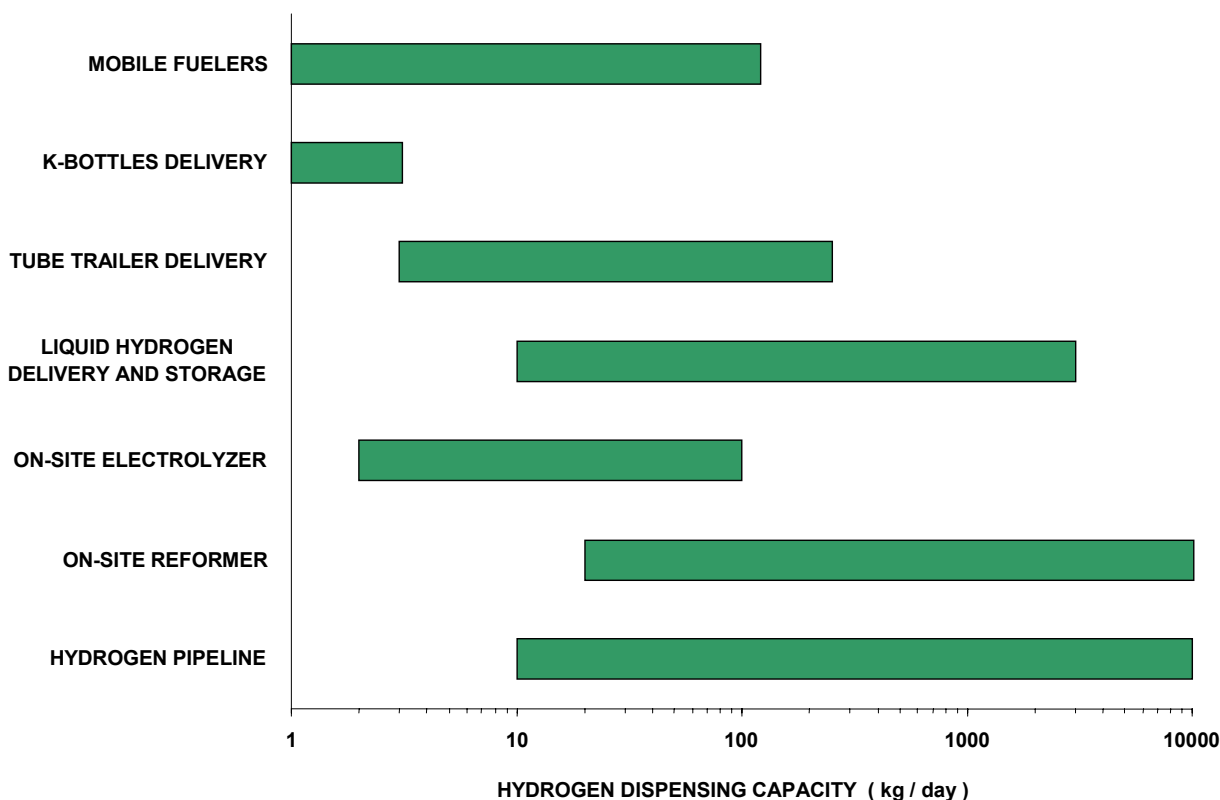
Figure 2-3. The ranges of hydrogen dispensing capacities appropriate to various types of fueling stations.

considerable "gray area" in the vicinity of the minimum and maximum dispensing capacities for each type of station. Table 2-3 summarizes the rationale for estimating capacity ranges as shown in Figure 2-3. It is likely that the ranges shown in Figure 2-3 will be narrowed down in the future as more hydrogen fueling stations are installed, additional operational experience and cost data are obtained, and community agreement evolves regarding which station types are best suited to various conditions.

The hydrogen pipeline-supplied fueling station option is a unique case. As previously discussed, only a few hydrogen pipelines currently exist in California, and these are relatively short and localized (e.g., connecting a production plant to a nearby customer such as a refinery). Therefore, this option is not generally available to station planners.

If it was available, a hydrogen pipeline could probably support capacities ranging from the minimum that would economically justify a connection to a maximum that exceeds the foreseeable needs of any one station.

Table 2-4 lists the numerical capacity ranges graphed in Figure 2-3 along with the estimates of the numbers of light-duty fuel cell vehicles or fuel cell transit buses that each type of station could support. The column indicating light-duty vehicles shows the number of vehicles that could refuel at the station, which is not the number of refuelings

Table 2-3. Summary of rationale for the hydrogen dispensing capacity ranges shown in Figure 2-3

Hydrogen Station Type	Approximate Minimum Practical Capacity		Approximate Maximum Practical Capacity	
	kg/day	Rationale	kg/day	Rationale
Mobile fuelers	1	Mobile fueler leasing assumed to be uneconomical for very low dispensing rates.	120	Largest planned mobile fueler has 120 kg of usable hydrogen capacity, and replacement more frequent that once per day is assumed to be uneconomical.
K bottles delivery	0	Cylinder rental is relatively inexpensive.	3	Tube trailer delivery/leasing more attractive if replacing more than one six-pack of K bottles per day.
Tube-trailer delivery	3	K bottle replacement more economical for lower dispensing rates	250	Approximate maximum useful tube trailer capacity, and replacements more frequent that once per day assumed to be uneconomical.
Liquid hydrogen delivery and storage	10	Vaporization venting losses excessive for small dispensing rates, and other options are more economical.	3,000	On-site production may be more economical if more than one tank truck delivery per day is required (depends on distance from plant).
On-site electrolyzer	2	Stations with small PEM electrolyzers have been built, but economics are anticipated to be relatively poor.	100	Estimate; future technology improvements and cost reductions of electrolyzers and renewable power generation may increase this number.
On-site reforming	20	Small-capacity reformers are routinely built for fuel cell systems. Gas processing requirements are more complex than for other approaches.	>10,000	An on-site reformer can accommodate the highest conceivable hydrogen station dispensing requirement (assuming an adequate natural gas supply).
Hydrogen pipeline	10	Not an option at this time unless adjacent to existing hydrogen pipeline.	>10,000	Not an option at this time unless adjacent to existing hydrogen pipeline.

Table 2-4. Example ranges of numbers of vehicles supported by various station types

Station Type	Hydrogen Usage (kg/day)	Light Duty Vehicles Refueling at Station	Transit Buses Fueled per Day
Mobile	1 – 120	1 – 180	1 – 8
Cylinders	0 – 3	1 – 4	0
Tube Trailer	3 – 250	5 – 380	1 – 16
Liquid Delivery	10 – 3,000	15 – 4,500	1 – 190
Electrolysis	2 – 100	3 – 150	1 – 6
On-site reformer	20 – 10,000	30 – 15,000	1 – 640
Pipeline	10 – 10,000	15 – 15,000	1 – 640

each day. For example, if ten light-duty vehicles regularly use a particular station, perhaps two would actually refuel on any given day.

2.2.3 Growth Considerations

Hydrogen fuel cell vehicle use is anticipated to expand rapidly. It may be prudent for fueling station designs to accommodate future dispensing capacity growth. There are several approaches to the growth issue and some types of stations can be expanded to higher capacities more easily than others.

One solution is to design the station for the expected growth instead of the near-term capacity requirement. This approach certainly increases initial cost, but it may result in lower life-cycle costs. This may not be an option if available funds are inadequate for a larger-capacity design. There is also the risk that the increased funds for the larger capacity are spent unnecessarily if the anticipated growth does not occur.

Some types of stations can be designed to minimize the incremental costs of future growth. For example, the civil work (i.e., concrete pads, paved areas, structures, utilities) and set-back distances of stations that receive and store liquid hydrogen can be designed to accommodate future installation of a second liquid hydrogen storage tank beside the original tank. The fueling island can be designed to accommodate additional hydrogen dispensers. Additional cascade or buffer high-pressure gas vessels can be added. Careful planning should address the tradeoffs involved in specifying higher-capacity compressors or liquid pumps versus subsequently installing additional compressors or pumps to accommodate growth.

Another approach to growth is to initially lease rather than purchase certain components. For example, the station can be designed to initially compress and

dispense hydrogen delivered and stored in leased tube trailers, and these can be replaced with a liquid hydrogen tank, electrolyzer, or reformer as the station dispensing demand grows. An even simpler variation on this strategy is to lease mobile hydrogen refueling equipment (to be discussed in Section 2.3.2.5) to support initial fleet operations, and then design and install a permanent station when requirements become more certain.

2.2.4 Station and Component Sizing

In order to properly service hydrogen vehicles, the station design must ensure that the station components can dispense the expected daily hydrogen usage in the fueling time available. There are two potential bottlenecks for the station. The first involves the production or storage of hydrogen, and the second pertains to hydrogen dispensing rates. These two factors are discussed in the following paragraphs.
Station designs using tube trailers or liquid hydrogen cryogenic tanks store quantities of hydrogen, which are periodically replenished when the tube trailers are replaced or the liquid tanks are refilled. The hydrogen is typically replenished on time scales longer than one day so the storage components must store significantly more than the daily hydrogen usage. Liquid hydrogen tanks can store very large quantities and do not limit the station throughput. Tube trailers store roughly 120,000 scf (275 kg) and mobile fueling concepts store considerably less. The daily hydrogen usage should generally be less than this amount; otherwise, the trailer or mobile fueler would have to be replaced too often.

Station designs using electrolyzers or on-site reformers produce hydrogen at a specified rate. If these components cannot produce hydrogen as quickly as the refueling requires, there is a potential bottleneck. Buffer or cascade storage (which is discussed subsequently) can ease the production requirement over short time intervals, but the overall daily hydrogen production capacity must be greater than or equal to the average daily dispensing requirement. Pipelines, when they are available, can provide very large flow rates and throughput. Reformers and electrolyzers have to be carefully sized to provide the minimum flow rates of hydrogen necessary to fuel the vehicles.

The second potential station bottleneck is the compressor or liquid pump. Stored or produced hydrogen either flows through a gaseous compressor or is pumped as liquid before being dispensed to vehicles. The flow rates of the compressor or liquid pump must not constrain the fueling process. Compressors must be carefully sized considering the station average and peak dispensing capacity requirements and any buffer or cascade storage vessels. Liquid pumps can more easily provide very high flow rates and they are not usually bottlenecks for refueling.

The following discussion provides some formulas useful for estimating compressor size and buffer storage size given vehicle-refueling parameters. The basic relations are analogous to those applicable to CNG fueling stations (Reference 7). Three types of fills are discussed: time fill, cascaded fast fill, and buffered fast fill.

A time fill procedure can be used when the time required to fill a vehicle is not a significant constraint. The compressor throughput is given by:

$$FR_{Comp} = N_N * \frac{V}{(T_F * N_C)}$$

Where FR_{Comp} is the flow rate of the compressor in scfm, N_N is the number of nozzles for refueling, V is the average volume of hydrogen per fill in scf, N_C is the number of compressors, and T_F is the fill time in minutes. T_F represents the amount of time to refuel a single vehicle. In a simple station with one compressor and one nozzle the compressor flow rate is simply the average volume of hydrogen per fill divided by the design time allowed for fills.

A buffered fast fill procedure is generally used to size compressors for constant refueling where vehicles wait in line to be refueled (such as in transit agencies). The compressor or compressors must be sized to fill each vehicle connected to a fill nozzle in the design cycle time (DCT) defined as the time between the start of one fill to the start of the next fill on the same nozzle. The compressor throughput is given by:

$$FR_{Comp} = N_N * \frac{V}{(DCT * N_C)}$$

Note that the design cycle time is the time of the actual fill plus the time between the end of the fill and the start of the next fill.

If there is a total fill time (TFT) available for fueling all the vehicles, the number of nozzles necessary can be calculated using:

$$N_N = N_V * \frac{DCT}{TFT}$$

where N_V is the total number of vehicles refueling.

When vehicles are moved into place and not being fueled, the compressor fills the buffer storage. If the buffer storage becomes full before the next vehicle can begin refueling, the buffer storage is undersized. This condition would extend vehicle fill times and not make the best use of the compressor. To ensure the buffer storage does not become full during constant fueling, the buffer storage is intentionally over sized. An idle protection factor (IP) can be used to estimate storage size. The buffer storage size, V_B, is given by:

$$V_B = \frac{IP * N_c * FR_{Comp} * T_D}{Eff}$$

where IP is roughly between 1.5 and 2, T_D is the dwell time or the time between the end of a vehicle fill and the start of the next fill, and Eff is the buffer storage efficiency. The storage efficiency is the percentage of storage volume that can be used to fill vehicles without contribution from the compressor. A reasonable value for Eff for buffer systems is 0.15.

A cascaded fast fill is used for stations that have peak fueling periods. During this peak period called the fueling window, FW, a significantly larger number of vehicles will fuel than at other times. The procedure to estimate compressor and storage cascade requirements assumes that both components share the fueling equally. The compressor begins filling the storage cascade T_L minutes after the start of fueling. During the first T_L minutes, the vehicle is filled from the storage cascade without the compressor active. The compressor maximum flow rate is given by:

$$FR_{Comp} = \frac{N_v * V}{2 * N_C * (FW - T_L)}$$

where N_v is the number of vehicles refueling during the time FW. The storage cascade total volume can be estimated by:

$$V_B = \frac{(N_v * V) - FR_{Comp} * (FW - T_L)}{Eff}$$

A reasonable value for Eff for cascade systems is 0.3. The storage cascade volume is the ratio of the total gas transferred to the vehicle minus that contributed by the compressor divided by the storage efficiency. Priority sequencing of high-pressure gas storage vessel cascades is discussed in Section 2.3.1.1.

In the discussion above the compressor capacity is calculated exactly. In practice, the compressor capacity could be specified choosing a compressor design that is more economical. Compressor cost is not a linear function of maximum flow rate. The cost increase is relatively small when the capacity is changed on a single compressor frame (which is analogous to a given internal combustion engine block that can have different bores and strokes). The jump to another frame is generally associated with a large increase in cost. Once a compressor capacity is calculated from the sizing equations, the cost – capacity relationship should be checked to see if the capacity can be increased with relatively little increase in cost. Increasing the compressor capacity could help prepare for future expansion. Another possibility is that the compressor capacity could be slightly reduced by moving to a smaller frame size and significantly reducing the cost.

The compressor and buffer or cascade storage sizing guidelines above apply to any station that receives or produces gaseous hydrogen, and they also apply to liquid hydrogen storage stations that vaporize and then compress hydrogen (as illustrated in

Figure 2-2C); however, stations that store and pump liquid hydrogen through a vaporizer to dispense compressed hydrogen (as illustrated in Figure 2-2D) do not need compressors and follow somewhat different sizing guidelines. In general, cryogenic pumps have much lower capital and operating costs than compressors with the same throughput capacities; however, most cryogenic pumps produce vapor (which must be vented or otherwise managed) during their starting and priming process, and so they usually should not be used in applications requiring frequent on/off cycling. Section 2.3.2.2 provides more details regarding liquid hydrogen pump applications.

Sizing liquid hydrogen storage tanks is subtle because so many factors are involved. An important specification for cryogenic tanks is the normal evaporation rate (NER), which is the percent of the tank capacity evaporated per day when the tank is vented at a specified pressure (usually one atmosphere). NER is less for larger tanks, but the product of the NER and capacity (i.e., the actual kg/day vented) is less for smaller tanks. As discussed in Section 2.3.2.2, it is possible to avoid venting altogether if deliveries of "fresh" hydrogen (with a low saturation temperature and pressure) are frequent, but this strategy is practical only for stations with high dispensing throughput. Similarly, it is more economical to purchase full hydrogen tank truck deliveries than partial loads. Hydrogen tank trucks typically hold 10,000 to 15,000 gallons, so a station storage tank of at least 15,000 to 20,000 gallons is needed to accommodate reasonable delivery scheduling uncertainties. Throughputs of over 1,000 gallons/day (200 kg/day) would be required to justify stations with tanks this large.

In general, for smaller throughput stations that store liquid hydrogen, the storage tank volume should be sized by balancing the economics of hydrogen delivery frequencies and quantities (which are better for larger tanks) against tank costs and venting rates (which are more favorable for smaller tanks).

2.3   Hydrogen Fueling Station Equipment and Integrated Designs

This section discusses the technical details of specific hydrogen fueling station design and equipment options. Hydrogen fueling dispensers are discussed first (Section 2.3.1) because they are common to all station designs. Section 2.3.2 reviews the basic types of integrated hydrogen fueling station designs (compressed hydrogen delivery, liquid hydrogen delivery, on-site reforming, on-site electrolyzers, mobile stations, and stations that dispense liquid hydrogen).

2.3.1 Compressed Hydrogen Dispensers

This section discusses compressed hydrogen dispensers because this component is common to all the compressed hydrogen dispensing station designs considered in Section 2.3.2. In Section 2.3.2.6, liquid hydrogen dispensers are considered as part of the liquid hydrogen fueling stations.

The design of compressed hydrogen dispensers has generally evolved from many years of experience with CNG dispensers. Many companies that manufacture CNG dispensers also market compressed hydrogen dispensers. These companies include Fueling Technologies Inc., General Hydrogen, FuelMaker, Kraus, and Tulsa Gas Technologies. Figure 2-4 shows an example of a compressed hydrogen dispenser.

The principal components of a compressed hydrogen dispenser are:

- The dispenser cabinet or housing
- User controls (or interface) and information display
- Fill nozzle(s)
- Hose(s)

Photograph courtesy Fueling Technologies Inc.

Figure 2-4.   Typical compressed hydrogen-fueling dispenser with two hoses providing 3,600 psi and 5,000 psi vehicle refueling capability

- Break-away connector(s)
- Flow meter and other transducers
- Control system
- Filter
- Tubing, valves, and various fittings
- Safety systems

Depending on the application and manufacturer, optional dispenser components may include:

- A card lock system or other access-control and payment device
- Priority-sequence control for cascaded gas storage vessels
- A second hose and nozzle (typically to dispense hydrogen to a different fill pressure)
- Heat-of-compression compensation algorithm
- Vehicle data interface and controls (e.g., CaFCP Type I interface, discussed in Section 2.3.1.4)

2.3.1.1 General Dispenser Components

Hydrogen dispensers can have a variety of outward appearances and housing designs. CNG experience has shown that the general public prefers that all automotive fueling dispensers resemble gasoline dispensers (e.g., Figure 2-4); however, this is not a factor for heavy-duty fleet vehicle refueling. Transit bus CNG dispensers sometimes do not look like public refueling CNG dispensers, and it is too early to predict what high-throughput hydrogen transit bus dispensers will look like.

The fill nozzle connects to the mating receptacle on the vehicle. Following CNG practice (Reference 8), a 5,000-psi nozzle can be connected only to a 5,000-psi receptacle, but a 3,600-psi nozzle can be connected to either a 3,600 or 5,000-psi receptacle. Sherex/OPC and WEH manufacture hydrogen fill nozzles. Figure 2-5 shows drawings of 3,600-psi and 5,000-psi receptacles. Both receptacles can accommodate a 3,600-psi nozzle, but the shorter 3,600-psi receptacle will not accommodate a longer 5,000-psi nozzle.

Compressed hydrogen fueling nozzles have a lever that actuates the three-way valve that allows gas (that would otherwise be trapped at the end of the fill) to be vented back to the dispenser through a vent hose. This makes it easier to disconnect the nozzle and minimizes the leakage of hydrogen (which is flammable and harmful to the ozone layer) from the nozzle and receptacle as the nozzle is removed.

Fill hoses are reinforced and rated for high-pressure hydrogen service. They should be replaced periodically (per the dispenser manufacturer's specification) as part of the station preventative maintenance program. The hose is connected to the dispenser by
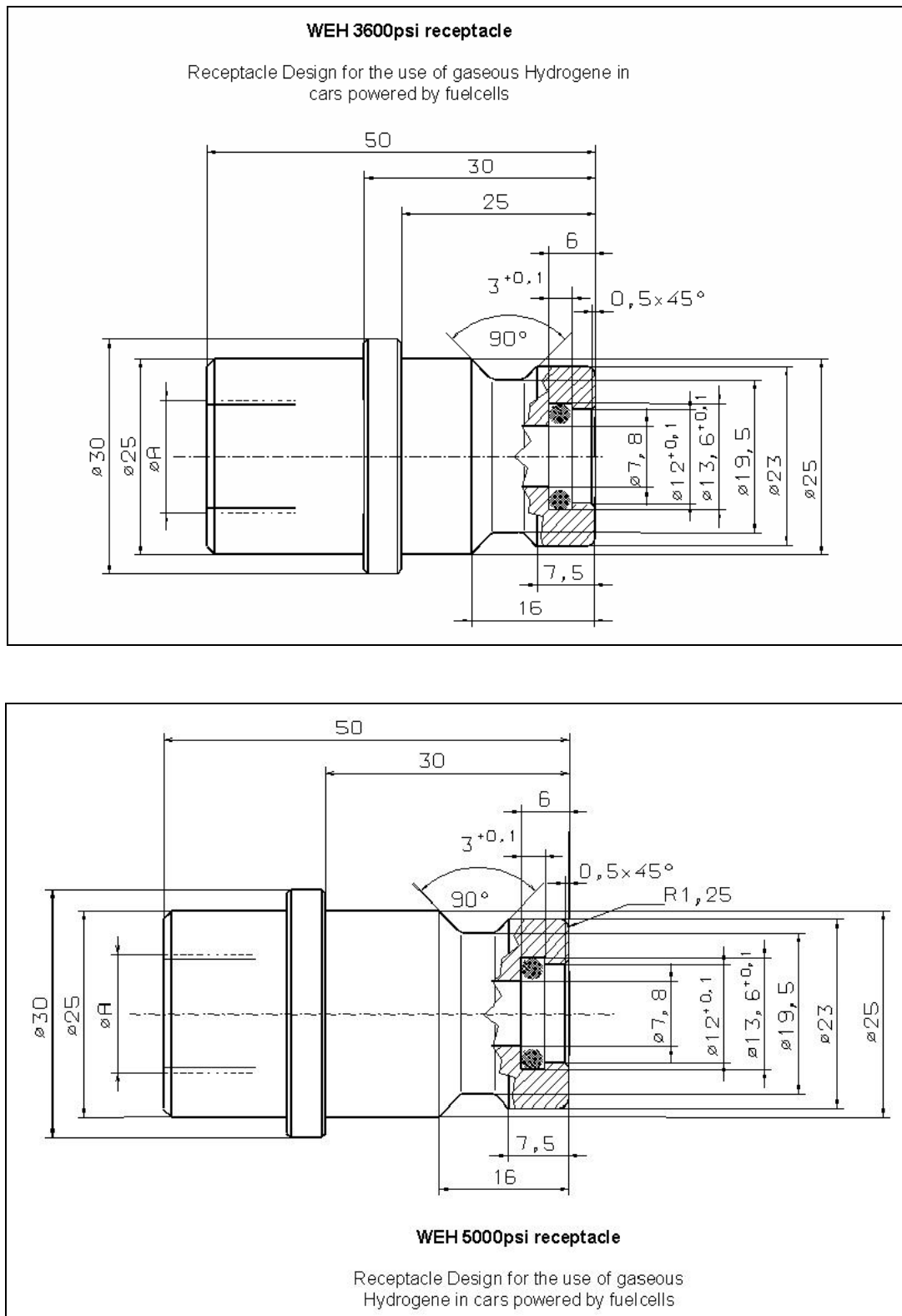
Figure 2-5.   3,600-psi and 5,000-psi hydrogen refueling receptacle configurations

a breakaway device. This coupling is designed to prevent hydrogen release in case a vehicle drives away from the dispenser with the nozzle still connected to the receptacle. The breakaway device disconnects when subjected to relatively low tensile loads or bending moments. Poppet valves in each segment spring closed to stop the hydrogen flow.

Most dispensers employ a Coriolis type of meter to measure the hydrogen gas flow rate (which is totalized to record the total quantity of hydrogen dispersed into the vehicle). MicroMotion (a division of Emerson Process Management) manufactures most of the Coriolis flow meters used in hydrogen and CNG dispensers. The advantage of this type of meter is that it directly measures the mass (not volume) flow rate of the fluid, and so no error-prone corrections are needed for temperature, pressure, and other effects. Also, they do not introduce a significant pressure drop, and their accuracy is reported as ±0.35 percent, with ±0.20 percent repeatability. The disadvantage of Coriolis flow meters is that they are expensive. Attempts have been made to use lower-cost orifice plates, turbine meters, and other flow-measuring devices in CNG dispensers, but these have not generally been successful. CNG dispensers have received California Weights and Measures approvals, but such approvals have not yet been sought for hydrogen dispensers.

2.3.1.2 Dispenser Safety Features

All compressed hydrogen dispensers include various safety features that are either required by applicable codes and standards, built in by the manufacturer, or options specified by the purchaser. Table 2-5 summarizes key safety features. Additional safety feature information is available from codes and standards documentation (Section 3.1) and from dispenser manufacturers.

2.3.1.3 Cascade Storage Priority-Sequencing Controller

All compressed hydrogen-fueling stations include some form of high-pressure gas storage prior to the dispenser. This storage is either a buffer or cascaded pressure vessel(s), and its capacity can range from small to large. Section 2.2.4 discusses buffer and cascade gas storage sizing, and Section 2.3.2.1 discusses the vessels themselves. If a high-pressure gas storage cascade is used, the controller for this cascade (which is called a priority-sequencing controller) is usually part of the dispenser.
Priority sequencing controllers have fully programmable set points for directing the gas supply from the different banks (i.e., at a common pressure) of storage vessels, or from the compressor, to the dispenser. The set points for switching the gas supply from different banks of storage vessels or the compressor are selected to suite the individual station component characteristics and fueling requirements. Set points are programmed based on an optimization considering:

- Storage pressure vessel number and capacity

- Compressor capacity
- Quantity of hydrogen to be dispensed into vehicles

Table 2-5. Summary of compressed hydrogen dispenser safety features

Safety Feature	Description and Purpose
Nozzle-receptacle compatibility	3,600-psi vehicle can be refueled only from 3,600-psi dispenser. 5,000-psi vehicle can be refueled from 5,000-psi or 3,600-psi dispenser. Prevents over-pressuring vehicle fuel tank.
Break-away coupling	In the event that a vehicle being refueled drives away with the nozzle connected, a device that connects the hose to the dispenser separates and valves close to preclude hydrogen flow from the hose or dispenser.
Access control	Access to a hydrogen dispenser may be controlled by a cardlock system, a keylock system, PIN access, or similar means.
Emergency shutdown device (ESD)	All fueling stations have an easily accessible ESD so that fuel flow to the dispenser(s) can be immediately terminated in case of an emergency.
Isolation valve	A normal-closed valve that opens when activated and closes due to de-activation, power loss, or ESD activation.
Excess flow valve	Some dispensers sense excessively high flow rates (e.g., due to a hose rupture) and terminate filling.
Hose integrity protection	Some dispensers include filling sequencing and algorithms that detect leaks and terminate filling.
Ground cables	Dispensers include a means to maintain a grounding connection with the vehicle during refueling.
Temperature-compensated fill control	Stops gas flow when fuel tank(s) reach the temperature-corrected fill pressure. Prevents tank over-pressure if vehicle is filled in cold environment and subsequently warms up. Explained further in Section 2.3.1.4. Not the same as heat-of-compression compensation.

- Number of vehicles to be filled in a given time frame
- Time specified to fuel a vehicle

Cascade storage with priority sequencing is beneficial for any station where the compressor capacity is significantly less than the desired dispensing flowrate, and it is especially important for stations with reformers or electrolyzers that typically have low-flow constant production capacities. As explained in Section 2.2.4, the utilization efficiency for a priority-sequenced storage cascade is typically 30 percent while the efficiency of simple buffer storage is typically 15 percent. The basic multi-bank cascade gas storage strategy and priority-sequenced control systems for compressed hydrogen storage are similar to those developed previously for CNG (e.g., Reference 7).

2.3.1.4 Heat-of-Compression and Ambient-Temperature Compensation

The heat-of-compression phenomenon and how this affects the ability to achieve full fills is one of the most frequently misunderstood aspects of compressed hydrogen and CNG refueling. In its simplest terms:

- Work must be done on the gas in the fuel tank to compress it to a high pressure. The gas that first enters the tank at low pressure gets a lot of work done on it, and the gas that enters subsequently receives less work.

- This work increases the internal energy of the gas, which manifests itself as a temperature increase.

- After refueling, the warm fuel tank slowly cools down as heat is transferred to its cooler surroundings.

- The decreasing gas temperature is accompanied by a pressure decrease, and this decrease continues until the gas temperature is equal to the ambient temperature.

- The "settled" pressure is less than the pressure immediately after refueling. If this pressure is less than the target fill pressure (e.g., 3,600 psi), the tank has been under filled.

Hydrogen is throttled as it flows through dispenser plumbing elements and into the vehicle tank; however, while throttling increases hydrogen's temperature (but it decreases methane's temperature,[2]), it has only an indirect effect on the heat-of-compression phenomenon. This is because throttling is an isenthalpic (i.e., constant enthalpy) process, and the entering gas enthalpy is the only property affecting the heat-of-compression. The main indirect effect is that throttling can increase or decrease the heat transfer to the gas (which affects its enthalpy) as it flows in the plumbing between the throttling elements and the vehicle tank.

Fuel tank pressure changes due to heat-of-compression effects are distinct from those due to ambient temperature changes. Pressure changes associated with ambient temperature changes are much more straightforward. If a hydrogen vehicle were slow-filled to 3,600 psi on a cold morning, and then it was left undriven in the sun as the day warmed up, the gas tank pressure would rise above 3,600 psi. To prevent this from occurring, codes requires that dispensers fill tanks to no more than the "temperature-corrected" fill pressure. The fill-pressure adjustment to compensate for ambient temperature changes is relatively straightforward.

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[2] This is because the Joule-Thomson coefficient (which is the temperature change per unit pressure change for a throttling process) is positive for methane but negative for hydrogen.

Compensating for the heat-of-compression effect is not as straightforward. The solution is to initially fill the tank to a higher pressure so that the settled pressure will equal the target fill pressure, but there are three basic challenges to actually accomplishing this:

- The fuel tank must not be over-pressured beyond its safe limits. This pressure limit depends on many factors including the tank design and applicable codes; however, hydrogen and CNG working groups have generally established this pressure limit (which is sometimes called the maximum vessel pressure) as 125 percent of the target settled pressure (which is sometimes called the reference pressure, e.g., 3,600 or 5,000 psi).

- The fuel tank pressure vessel must not be overheated. In particular, the composite materials used in Type III (overwrapped metal liner) and Type IV (all composite) tanks degrade at higher temperatures. The temperature limit for composite tanks is frequently cited (e.g., References 9 and 10) as 180°F or 185°F.

- It is not straightforward to compute the fill pressure that will yield the desired settled pressure. The reasons for this and the techniques for increasing the probability of a full fill are discussed subsequently.

Figure 2-6 illustrates the heat-of-compression effect and compensation to achieve a full fill at a settled pressure of 3,600 psi. This is a simulation of filling a 200-liter Type III tank at 1 kg/min for the conditions shown on the graph. The simulation (Reference 11) accounts for the significant heat transfer events (from the gas to the tank and from the tank to the environment) and it has been checked against experimental data generated
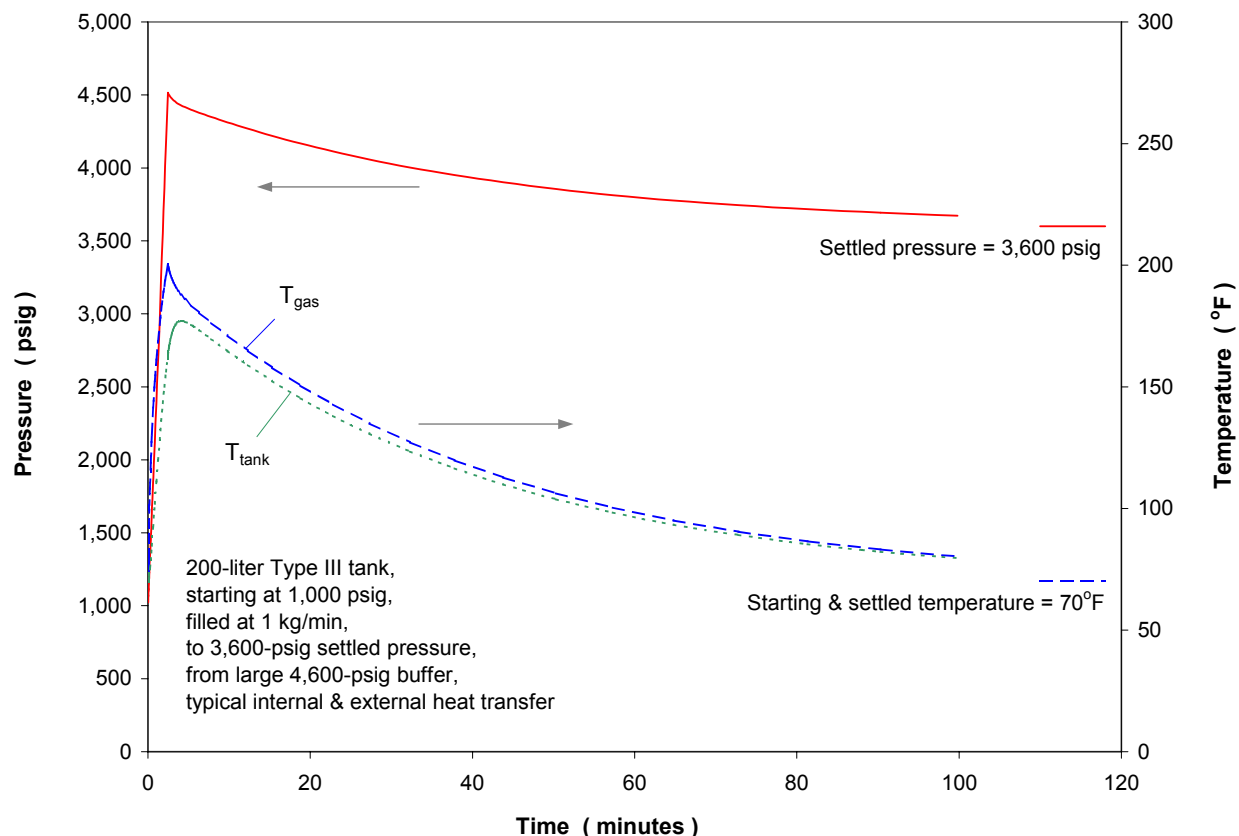
Figure 2-6. Illustration of heat-of-compression effect and compensation to achieve a settled pressure of 3,600 psi

by the Gas Technology Institute (Reference 12). The tank cools off and the pressure decreases much more slowly than it heats up during filling. The filling is stopped when the pressure reaches 4,500 psi (125 percent of 3,600 psi) in 2.45 minutes, which exactly compensates for the heat-of-compression so that the pressure eventually settles to 3,600 psi. The gas temperature peaks at 200°F and the tank temperature peaks at 177°F in this example.

The heat-of-compression effect increases when the tank is relatively empty (low pressure) at the start of the fill and for higher target settled pressures (e.g., 5,000 relative to 3,600 psi). It also increases for faster fill rates and for tanks with low thermal capacity and conductivity (e.g., Type IV).

In practice, the challenge is to know when to stop the fill in order to compensate for the heat-of-compression to achieve the desired settled pressure (i.e., a full fill). Table 2-6 lists some of the factors that contribute to this challenge. Two approaches to heat-of-compression compensation are being pursued to overcome these problems: compensation algorithms (sometimes called electronic temperature compensation) that

predict the needed fill pressure, and control systems that receive tank data transmitted from the vehicle to the dispenser (such as being developed by the CaFCP). Table 2-6 briefly summarizes these two approaches.

Table 2-6. Factors that complicate heat-of-compression compensation

- Many variables affect the tank pressure rise rate during filling: fill rate, tank volume, initial pressure and temperature, entering gas enthalpy, and tank heat transfer characteristics

- The tank volume is not ordinarily known by the dispenser

- During fast-filling, the pressure measured at the dispenser is unequal to the tank pressure due to various highly variable pressure drops

- The enthalpy of the gas entering the tank is affected by the cascade/buffer/compressor characteristics, metering elements and other fittings in the fill lines, and heat transfer to/from these lines

- Variables include the heat transfer from the gas to the tank (relatively fast), the thermal capacitance and conductivity of the tank (depends on the type of tank), and heat transfer from the tank to its surroundings (mostly free convection, which is relatively slow)

- GTI tests show that the gas temperature and heat transfer inside the tank is nonuniform

Compensation Algorithms

Heat-of-compression compensation algorithms seek to predict the quantity of gas to be dispensed into the fuel tank (or some other fill-stop parameter) that will provide a full fill or the fullest possible fill within tank pressure and temperature constraints. These algorithms perform calculations without any direct measurements of fuel tank quantities (e.g., volume, temperature, pressure) that are transmitted back to the dispenser. Therefore, they must incorporate various estimations and approximations because there are not enough *known* quantities to compute all the *unknown* quantities while accounting for all the effects listed in Table 2-6. A very important quantity that is difficult to measure accurately during fast filling is simply the vehicle tank pressure. This is because the pressure drop between the pressure transducer in the dispenser and the vehicle tank can be substantial and it is affected by many factors including the vehicle fuel system design and the filling conditions. Some algorithms estimate this pressure drop from measurements at the beginning of the fill, and other algorithms cause the dispenser to pause (briefly stop filling) at some point during the fill to measure the vehicle tank pressure (because the dispenser pressure is equal to the tank pressure when there is no flow).[3] The algorithms estimate quantities related to the vehicle tank volume and heat transfer based on the inferred pressure rise rate, and this information is incorporated into the calculation that signals the dispenser when to stop filling.

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[3] The CaFCP Type II and Type III fill protocols (i.e., those without vehicle tank pressure and temperature signals) include a 10-second pause when the target fill pressure (which is compensated for ambient temperature but not heat-of-compression) is reached. If the pressure measurement drops below the target fill pressure, then filling resumes. Otherwise, the dispenser displays "Fill Complete."

Fueling Technologies, Inc. (Reference 10), the Gas Technology Institute (Reference 12), and Marathon Technical Services (Reference 13) have developed heat-of-compression compensation algorithms of this type.

Filling with Vehicle Data Transmission

Heat-of-compression compensation algorithms without vehicle data transmission are used routinely at CNG fueling stations. Their accuracy is generally acceptable but not perfect. Heat-of-compression compensation is more critical for hydrogen than for CNG for three reasons:

- The thermodynamic properties of hydrogen and methane are such that, during tank filling under comparable conditions, hydrogen becomes hotter and its pressure usually increases faster (depending on the specific filling conditions) than natural gas.

- Some hydrogen vehicle tanks are filled to 5,000 psi while the maximum CNG vehicle fuel tank pressure is 3,600 psi. Heat-of-compression effects become more pronounced at higher fill pressures.

- Because the volumetric energy density of hydrogen is less than that of natural gas, the implications of under-filling hydrogen fuel tanks due to heat-of-compression effects are more profound.

For these and other reasons, the CaFCP has developed a Fueling Interface Specification (Reference 14) that includes a protocol (defined as a Type I fill) for refueling with vehicle fuel tank data transmitted to the dispenser. This case is sometimes referred to as the vehicle communications option (VCOMMS). The CaFCP protocol specifies the quantities transmitted from the vehicle to the dispenser (tank volume, pressure, temperature, and other control signals), and it specifies the details of the cable and connector plug (Figure 2-7).

Figure 2-7.   The CaFCP Vehicle-Dispenser Communications Connector

The information transmitted from the vehicle to the dispenser enables relatively exact calculations to be carried out to compensate for heat-of-compression effects. Full fills of compressed hydrogen tanks during fast filling are often limited by the previously discussed tank temperature and pressure limits. Reference 14 provides details of the CaFCP Type I filling protocol for heat-of-compression compensation within these limits.

2.3.2 Types of Hydrogen Fueling Stations

Specific technical information regarding different types of integrated hydrogen fueling station designs is presented here. Stations that receive and store hydrogen delivered as a compressed gas and cryogenic liquid are discussed in Sections 2.3.2.1 and 2.3.2.2, respectively. Stations that produce hydrogen on-site by reforming natural gas (or some other hydrocarbon feedstock) or electrolysis are discussed in Section 2.3.2.3 and 2.3.2.4, respectively. Mobile hydrogen fueling stations are discussed in Section 2.3.2.5. Stations that dispense only liquid hydrogen are considered separately in Section 2.3.2.6.

2.3.2.1 Compressed Hydrogen Delivery

Delivering compressed hydrogen to a fueling station provides a refueling option that can be implemented relatively quickly with a low capital cost. Delivered sources of compressed hydrogen include both cylinders delivered by truck and tube trailers. This

section describes compressed hydrogen storage and compression options. Dispensers were discussed in Section 2.3.1.

Tube Trailers and Compressed Gas Cylinders

Hydrogen tube trailer fueling stations are a simple, relatively inexpensive way to provide hydrogen fueling for vehicles. Hydrogen gas is stored in the tube trailer, which feeds a compressor. After compression, the gas is stored in buffer or cascaded storage tanks and then dispensed to the vehicles. The trailer assembly is typically not a permanent fixture since it is refilled off site when empty. Connections to the trailer utilize a flexible hose while permanent tube trailer installations are typically connected with rigid tubing.

A tube trailer consists of a pack of pressurized cylinders connected by a manifold and housed on a trailer. Tube trailers hold roughly 120,000 scf (280 kg) of hydrogen at pressures in the range of 2,400 to 3,100 psi. Typical dimensions for the trailer are 40 to 45 feet long, 10 feet high, and eight to nine feet wide. When installed, the trailer is supported by a wheel assembly on one end and landing gear on the other. Figure 2-8 is a simplified diagram of a tube trailer and tractor.
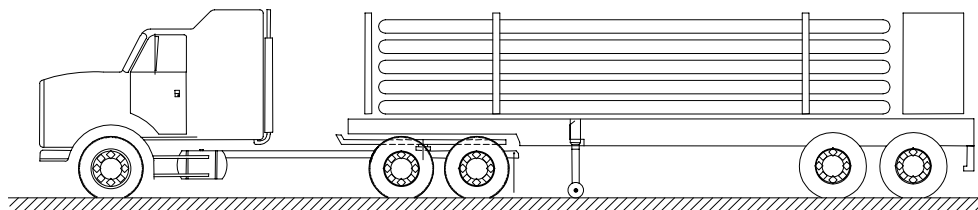
Figure 2-8.   Compressed gas tube trailer and tractor

Hydrogen can also be delivered in compressed gas cylinders. Industrial gases are typically compressed to 3,000 psi in a variety of storage vessels. The standard "K bottles" hold 300 scf of hydrogen with a water capacity of 1.8 ft^3. K bottles are often combined in a six pack, which would hold 1,800 scf or 4.3 kg of hydrogen. Industrial gas companies deliver K bottles by truck. Hydrogen delivery and storage in K bottles may be an attractive option for temporary stations or stations with an extremely low throughput. Of course, if hydrogen vehicles are to be filled completely (i.e., to their maximum pressure) or if the K bottle capacity is to be utilized efficiently, then they must be connected to a compressor similar to the arrangement previously discussed for tube trailers.

Delivered Compressed Hydrogen Stations

Compressed hydrogen delivery is often chosen when the fuel dispensed per day is relatively low and when the station capital cost must be kept low. The hardware may be

leased or included in the price of the hydrogen. This may be a good choice for relatively short demonstration projects with a low number of vehicles.

The scale of the fueling station and delivery options depends on the expected vehicle demand with a six pack of K bottles containing enough hydrogen for one vehicle fueling and a tube trailer holding enough hydrogen for several weeks of passenger car fueling. The useful mass of hydrogen stored in a tube trailer is roughly 250 kg. The entire volume of hydrogen is not available because the suction pressure of the compressor is not zero and trailers must be scheduled for swapping to prevent running out of hydrogen fuel.

Stations planned for initially small fleets that are expected to grow considerably with time can also benefit from using tube trailers. These stations could be designed for tube trailers in the early phase when the required hydrogen throughput is modest. When the number of vehicles served by the station grows and the hydrogen consumption increases, the tube trailer can be replaced by another option for hydrogen production or storage such as reformers or liquid hydrogen cryogenic tanks. The initial station design should account for the possible transition from tube trailers to other hardware.

One concern in designing the station for future upgrades in capacity is the inlet (suction) pressure of the compressor. Tube trailers store hydrogen at 2,400 to 3,100 psi, dropping in pressure as hydrogen is consumed. A regulator allows the tube trailer to supply hydrogen at the compressor suction pressure. A fixed suction pressure is a practical approach for operating the compressor. If the station will be upgraded to another hydrogen source, the output pressure from the new hydrogen supply must be considered in the design of the compressor. Reformers generally supply hydrogen at relatively low pressure. Therefore, compressors for stations with reformers must be designed for suction pressures below 150 psi. Electrolyzers can potentially provide higher output pressures.

A tube trailer fueling facility at the National Fuel Cell Research Center (NFCRC) at U.C. Irvine is shown in Figure 2-9. The fueling station is equipped with a tube trailer, high-pressure storage, and a compressor. The upper photograph in Figure 2-9 shows a tube trailer in the background with a K bottle six pack in the foreground. The lower photograph shows the tube trailer and a fuel cell vehicle.

Station Siting Issues

Tube trailer siting considerations include meeting safety standards and allowing for trailers to be swapped. The site must meet NFPA 50A standards for gaseous hydrogen. All electrical devices within 15 feet of the trailer must be explosion proof and meet NFPA 70 Class 1, Group B, Division 2 standards. The minimum distance to buildings or

Figure 2-9.   The NFCRC hydrogen fueling station at U.C. Irvine utilizes K bottles and a tube trailer.

streets is 25 feet. The trailer should be properly grounded. Crash protection such as bollards should be placed around any vehicle access to the site.

When an empty trailer must be replaced, a tractor hauling a full trailer will be brought to the site and the trailers will be swapped. This process requires temporarily parking the full trailer in a suitable area, bringing the empty trailer to another suitable area, and finally installing the full trailer. Swapping trailers thus requires considerable area. The station footprint must allow access to the tractor and trailer together (roughly 60-70 feet in length). In addition, the station must include enough space to allow for the tractor-

trailer turning radius so the vehicle can access both the temporary drop site and the station location.

Stationary Storage Requirements

Requirements for compressed gas storage depend on their use, storage pressure, and capacity. A primary distinction among storage vessels is their type of certification. Storage vessels can be certified to meet American Society of Mechanical Engineers (ASME) or Department of Transportation (DOT) requirements. The ASME certification is typically required for stationary applications (as specified by California Code of Regulations Title 8) and DOT certification is usually required for vessels that are used to transport compressed or cryogenic gases such as hydrogen. (Section 3.1.1.3 provides additional information regarding pressure vessel certification and application.)

DOT Vessels

DOT-certified pressure vessels are intended for applications that require over the road transport. Tube trailers and K bottles are typically DOT-certified, although ASME certified configurations are also possible. A typical application for a DOT-certified vessel would be hydrogen that is transported by tube trailer and temporarily parked at a fueling facility and removed when the trailer is empty.
DOT vessels have some characteristics that are different from ASME vessels. Since DOT vessels are designed for over-the-road transport, they are typically a light-weight design (compared to some ASME vessels where weight is not a consideration). DOT regulations require that a burst disc/fusible metal pressure relief device (PRD) provide over pressure protection. This device is screwed directly into the bottle with a vent line that directs vented gas to a safe location. Several types of DOT cylinders are built. Type I steel cylinders must be inspected and hydrostatically tested every five years. Type IV cylinders are made of all composite material and must be visually inspected every three years.
Various applications of DOT cylinders apply to hydrogen fueling stations. The most straightforward is a temporary use of the cylinders at a fueling station while hydrogen is being consumed. DOT cylinders have been used for permanent storage at some CNG fueling stations in Canada under very specific constraints. Anyone considering the use of DOT cylinders for permanent storage should consult with state and local safety, fire, and code officials.

ASME Vessels

ASME Section VIII, Division 1, Unfired Pressure Vessels provides the requirements for stationary pressure vessels for hydrogen storage. ASME codes typically apply to any vessel with an internal pressure that exceeds 15 psig with a cross section diameter

greater than six inches; vessels smaller than six inches fall under ANSI piping requirements.

ASME certified vessels have requirements that distinguish them from DOT vessels. The ASME Section VIII, Division 1 certification results in a design that does not require recertification or periodic testing.

ASME vessels are equipped with a reseatable relief valve and/or a burst disk rather than a PRD. The vessels are readily designed for 6,250 psig storage, which provides sufficient pressure to fill vehicles rated for 5,000 psig storage. The storage pressure is typically specified at 1.25 times the vehicle rating because this is the maximum pressure for vehicle fueling. ASME vessels are available in much larger sizes than DOT vessels because weight is not a consideration for stationary storage. The most common ASME vessels are long cylinders with diameters up to 24 inches. Figure 2-10 shows a tube trailer parked beside two ASME pressure vessels at the SunLine Transit hydrogen fueling facility in Thousand Palms, California.

Compressor Requirements and Options

The physical properties of hydrogen, fuel purity specifications for fuel cell vehicles, hydrogen supply, and vehicle fuel storage pressure affect the requirements for compressors. The principal factors to consider in a fuel station design include the type of compressor, motor, and pressure requirements.

Figure 2-10.   Hydrogen Tube Trailer and ASME Vessels at SunLine Transit

Compressor design options include the cylinder lubrication system, cooling system, motor, and piston configuration. Oil-free compressors are generally preferred for hydrogen compression over oil-lubricated designs because lubricating oil is a source of contamination for the hydrogen. Cooling between compression stages can be accomplished with air or coolant. Air-cooled compressors are less complex but the cooling, cylinder life, and to some extent power consumption, are improved with water-cooled designs.

To date, most CNG and hydrogen fueling stations utilize electric motor driven compressors. While some CNG stations have natural gas engine powered compressors, it is usually challenging for both design requirements to meet codes and emission permitting. Pneumatic or hydraulic driven compressors (which are usually called intensifiers) are an option for some hydrogen fueling station applications. The compressor at the U.C. Irvine NFCRC hydrogen fueling station is driven by compressed air. Intensifiers are also being considered to provide a "boost" stage downstream of a motor-driven reciprocating-piston compressor (e.g., if a 4,500-psi CNG compressor is adapted to a 6,250-psi hydrogen application).

Reciprocating piston compressors require multiple compression stages to achieve final delivery pressure. A piston compresses the gas in each stage. The gas is then cooled before it enters the next stage. There are different requirements for compressing hydrogen than for compressing natural gas for vehicle use. A CNG compressor is typically four stages with a final delivery pressure of 4,500 psi. For passenger car fueling at 5,000 psi, the hydrogen compressor needs to provide hydrogen at up to 6,250 psi.

Typical hydrogen compressors will have more stages than CNG compressors. The additional stages are due to the higher output pressure and physical properties of hydrogen. The gas properties of hydrogen also affect the exit temperature for each compression stage. Compressors need to be designed to limit the exit temperature for each stage so that material and thermal stress limitations are not exceeded. The exit temperature for a compression stage can be approximated by the formula for isentropic compression:

$$T_e = T_i (r)^{(\gamma - 1)/\gamma}$$

Where:

T_e = exit temperature
T_i = inlet temperature
γ = isentropic coefficient
r = compression ratio

For hydrogen, the isentropic coefficient is 1.4 compared with a value of slightly less than 1.3 for natural gas (depending upon the composition). The higher isentropic coefficient for hydrogen requires lower compression ratios in order to limit the exit temperature from each stage. The compressor exit temperature needs to be limited to approximately 300°F to ensure acceptable durability.

Diaphragm compressors are an alternative to piston compressors. They are often preferred for hydrogen service because they provide a better seal than piston compressors. While diaphragm compressors have maintenance and performance advantages over piston compressors, they are also considerably more expensive. Figure 2-11 shows a diaphragm compressor at the SunLine Transit hydrogen fueling station.

The power required for hydrogen compression depends on the compressor inlet and exit pressure, compressor configuration, and motor efficiency. The energy consumption can be approximated by summing the work required for each stage in a multi-stage compressor and taking into account compressor and motor losses. Compressing hydrogen to 6,250 psi from a 150 psi source requires about 3 kWh/kg.

Figure 2-11. Diaphragm compressor at SunLine Transit

2.3.2.2 Liquid Hydrogen Delivery

Liquid hydrogen is the other alternative (besides compressed hydrogen gas, which was discussed in Section 2.3.2.1) for transporting and storing hydrogen at a fueling station. When hydrogen at atmospheric pressure is cooled to -423°F and its heat-of-vaporization is removed, it condenses to a liquid. There are two merchant[4] hydrogen production and liquefaction plants in California. A plant in Sacramento is owned and operated by APCI; a plant near Ontario is owned and operated by Praxair. These plants produce hydrogen via steam reforming of natural gas as discussed in Section 2.3.2.3. The hydrogen is then liquefied for convenient transportation to customer sites. The

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[4] "Merchant" denotes the fact that these plants produce hydrogen for delivery and sale to retail customers. There are other hydrogen plants in California, but these are dedicated to co-located customers or owned by the hydrogen user.

liquefaction process usually utilizes a multi-stage cycle (Reference 4) to maximize efficiency. It also includes catalytic conversion of ortho to para hydrogen, which is necessary so that this slow exothermic reaction does not occur in the liquid hydrogen storage tank and cause excessive boil-off.

The primary advantage of liquid hydrogen transportation and storage is its relatively high density. As shown in Figure 2-1, the density of liquid hydrogen saturated at 10 psig (which is typical for truck-transported hydrogen) is 4.28 lbm/ft^3. This is approximately 3.8 and 2.9 times the density of 60°F hydrogen gas compressed to 3,600 psig and 5,000 psig, respectively. The main disadvantages of liquid hydrogen are associated with its very low temperature. Special cryogenic equipment is required to produce, store, and process liquid hydrogen. Even with this cryogenic equipment, some boil-off loss inevitably occurs at various points in the infrastructure chain. This boil-off loss can be negligible for fueling stations with a high throughput, but it can be substantial for low-throughput stations (e.g., where liquid hydrogen deliveries are less frequent than once per week). Additional consideration of boil-off losses is included in subsequent discussions of fueling station design and components.

Liquid hydrogen is the most appropriate delivery and storage mode for fueling stations that will dispense only liquid hydrogen into vehicles. The design of liquid-hydrogen-dispensing stations is discussed in more detail in Section 2.3.2.6.

A number of stations that receive and store *liquid* hydrogen in order to dispense *compressed* hydrogen have been designed and installed, but all of these have relatively low capacities and throughputs (e.g., compared to a transit fleet diesel fueling station). One of the first such hydrogen fueling stations in the U.S. was the Chicago Transit Authority station, which supported their pioneering fuel cell bus demonstration in 1997 (Reference 15). The hydrogen fueling station at the Xerox Corporation site in El Segundo, California, supplemented their solar-powered electrolysis production with liquid hydrogen delivery and storage. The Chicago Transit and Xerox stations are no longer operating. An example of a currently operating station in California that receives and stores liquid hydrogen while dispensing both compressed and liquid hydrogen is the CaFCP station at the Partnership's headquarters facility in West Sacramento (Figure 2-12). A profile of the CaFCP station, which details its specifications and features, is included in Appendix A. The Valley Transportation Authority (VTA) hydrogen fueling station in San Jose, California, is an example of a planned compressed hydrogen fueling station that will receive and store liquid hydrogen. The contract for this station was recently awarded to APCI based on their proposal to design and install the station and to supply the liquid hydrogen.

All hydrogen fueling stations in this category receive liquid hydrogen delivered in cryogenic tank trucks, which typically have a capacity of 10,000 to 15,000 gallons. They all also store the liquid hydrogen in cryogenic vessels, which will be described subsequently. There are important design options for processing this liquid hydrogen in order to dispense compressed hydrogen into vehicles. Figure 2-2C and D sketched two of these options. Figure 2-2C sketches an option involving vaporization and warming of the low-pressure liquid hydrogen, compression of this gas to high pressures, storage of

the compressed gas in a high-pressure vessel cascade or buffer, and dispensing to vehicles. The option sketched in the fourth diagram in Figure 2-2D consists of pumping the cryogenic liquid hydrogen to a high-pressure supercritical state, warming this supercritical fluid to near-ambient temperatures in a heat exchanger, storage of this high-pressure gas in a cascade or buffer, and dispensing to vehicles. A third option, which is a combination of the first two, is to use a pump for most of the

Figure 2-12.   The CaFCP hydrogen fueling station in West Sacramento is an example of a station that receives and stores liquid hydrogen and dispenses compressed and liquid hydrogen.

station throughput and a compressor for boil-off vapor management. These options and their tradeoffs are discussed below.

A fourth option is to employ a special cryogenic pump that can process either liquid or vapor or liquid-vapor mixtures. Such pumps, which may be thought of as pump-compressor combinations, can draw vapor to reduce the liquid hydrogen storage tank pressure (and therefore mitigate the need for vapor venting), or they can pump liquid. An example of such a pump is the cryogenic hydrogen compressor (CHC) manufactured by APCI (Reference 16). A CHC was used at the previously-mentioned Chicago Transit hydrogen fueling. The discharge flow rate of this type of single-stage pump-compressor is substantially less when pumping vapor than when pumping liquid, and this must be taken into account in station planning and design. Multi-stage high-pressure cryogenic pumps that can maintain full flow rates while processing high

fractions of saturated vapor have been developed and demonstrated (Reference 17), but they are not commonly available commercial products.

Figure 2-13 illustrates the important difference between the pump-and-warm option and the vaporize-and-compress option. This graph shows the pressure (with a logarithmic scale) versus the enthalpy for each path. Enthalpy is a thermodynamic property that represents the energy in the flowing fluid. For example, the minimum
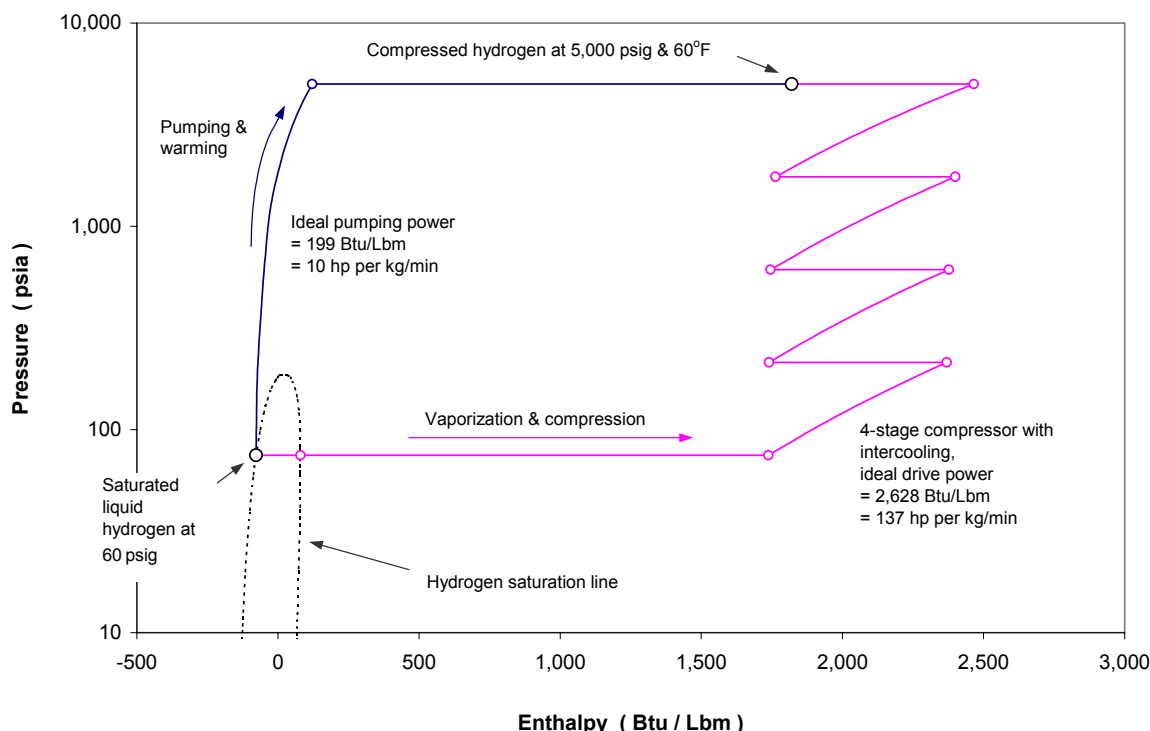
Figure 2-13. Pressure versus enthalpy for equilibrium hydrogen, illustrating two alternative paths for dispensing compressed hydrogen from stored liquid hydrogen

(ideal) power required to pump or compress a flowing fluid is equal to its mass flow rate times its enthalpy change.

Figure 2-13's broken-line curve is the hydrogen saturation "dome." Hydrogen is a liquid to the left of the dome, a vapor to the right, and a liquid-vapor mixture within the dome. Hydrogen's critical point is at the peak of the dome, and hydrogen above this point is said to be supercritical. In Figure 2-13, the hydrogen is assumed to be stored at a saturation (i.e., the liquid and vapor are in equilibrium) pressure of 60 psia, which is approximately 74.7 psig. The near-vertical line denotes the pressure and enthalpy change of saturated liquid hydrogen as it is pumped from 74.7 psig to 5,000 psig. For simplicity, this path is assumed to be isentropic, i.e., without friction or heat transfer. As shown in this graph, the required pumping power per unit flow is 199 Btu/lbm, or

approximately 10 hp per kg/min. Real pumps have various losses and inefficiencies, and so the actual pumping power will be somewhat higher. The horizontal line extending across the top of Figure 2-13 represents the warming of the supercritical hydrogen (which exits the pump at approximately -390°F) to 60°F as it flows through the heat exchanger.

The vaporize-and-compress option starts with the horizontal line extending to the right from the liquid side of the dome in Figure 2-13. This line denotes vaporization of the liquid hydrogen (from the left to the right side of the dome) followed by warming of the hydrogen gas to 60°F. The ambient-temperature 74.7-psig hydrogen is assumed to be compressed to 5,000 psig in a four-stage compressor with intercooling after each stage. The need for multiple stages with intercooling to compress hydrogen to high pressures was discussed in Section 2.3.2.1. For simplicity, each of the four compression stages is assumed to be free of friction and heat transfer, and the cooling stages are assumed to occur without any pressure loss. The total ideal compression power requirement is the sum of the four stages: 2,628 Btu/lbm, or approximately 137 hp per kg/min. Real compressors have various inefficiencies that cause the actual power requirement to be somewhat more.

This example illustrates that the strategy of pumping liquid hydrogen to high pressures and then warming it to ambient temperatures is substantially more energy efficient (and requires less expensive equipment) than the option of vaporizing liquid hydrogen and then compressing it. The advantage of the vaporize-and-compress strategy is that it produces less boil-off vapor and it can process some or all of the vapor that must be vented if a pump is used.[5] Boil-off vapor is a particular problem for liquid hydrogen because its heat-of-vaporization and saturation temperature are both relatively low. The heat-of-vaporization is the width of the vapor dome in Figure 2-13, which is 157 Btu/lbm at 74.7 psia. This means that approximately one pound of hydrogen is vaporized for every 157 Btus that are transferred to the liquid. A vaporize-and-compress system is able to remove vapor from the liquid storage tank and therefore mitigate boil-off venting. The capacity of this station type to process boil-off vapor depends on the available storage capacity. In addition to boil-off due to heat leaks into the hydrogen storage tank, stations that use cryogenic liquid pumps experience additional vaporization associated with the need to cool down the pumps or maintain them at a low temperature so that they are primed with liquid.

A tradeoff analysis should be carried out considering each liquid hydrogen storage station's particular set of circumstances in order to determine if the pump-and-warm or vaporize-and-compress design is more suitable. In general, stations with a high and steady hydrogen throughput can benefit from the efficiency, simplicity, and economics of the pump-and-warm design. Conversely, for stations with a low and/or irregular hydrogen throughput, this design results in unacceptable product vented vapor loss,

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[5] An exception is the previously mentioned cryogenic pump-compressor combinations that can process liquid and vapor mixtures.

and the vaporize-and-compress design is more suitable. The previously mentioned CHC system may be applicable to intermediate- and possibly high-throughput stations, and an independent evaluation of the Chicago Transit station operating data would be helpful for establishing this.

Figure 2-14 is a simplified schematic of a hydrogen fueling station that receives and stores liquid hydrogen, dispenses compressed hydrogen, and uses the previously
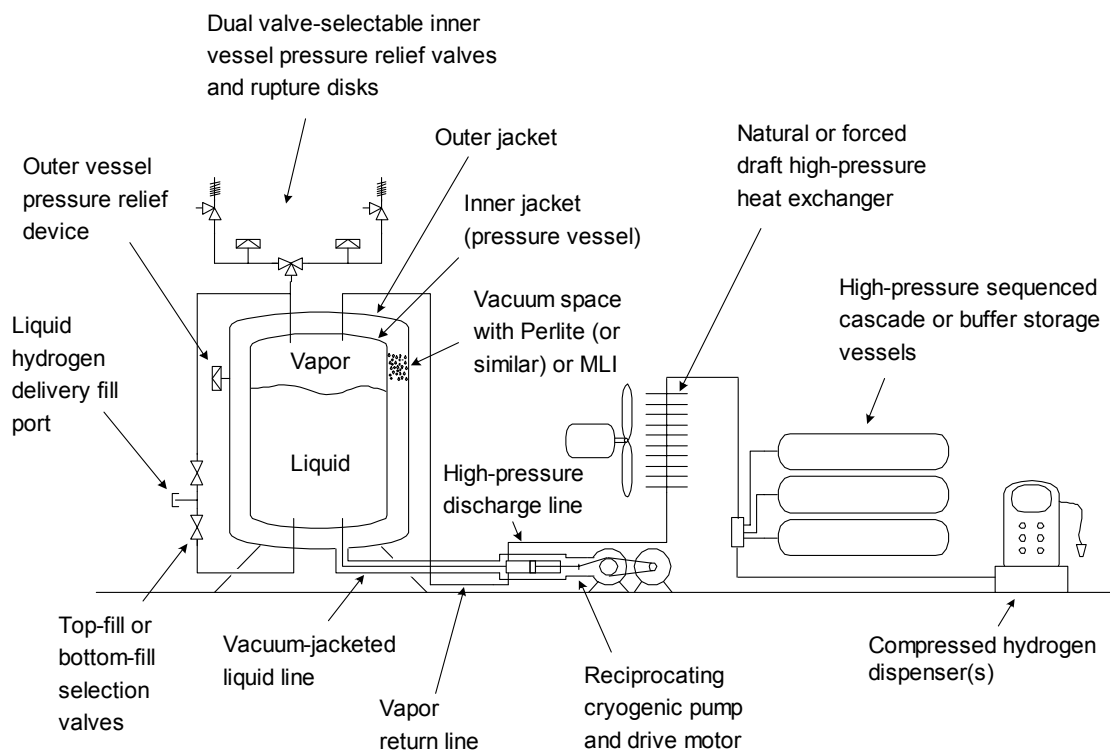
Figure 2-14. Simplified schematic for a hydrogen fueling station that receives and stores liquid hydrogen, pumps and warms the hydrogen, and stores and dispenses compressed hydrogen gas

discussed pump-and-warm design strategy. This diagram illustrates the principal components of such a station and how they are integrated. Figure 2-14's tank and pump circuit is shown in more detail than the compressed hydrogen storage vessels and the dispensers because these components are identical to those discussed in prior sections of this report.

The liquid hydrogen storage tank is obviously a key component. Liquid hydrogen tanks are available as shop-fabricated cryogenic vessels in sizes up to approximately 50,000 gallons. Companies such as Chart Industries (Reference 18) and Taylor-Wharton (Reference 19) manufacture standard sizes of horizontal or vertical tanks, and they can custom-fabricate tanks of other sizes and configurations. All cryogenic hydrogen tanks

of this type are of vacuum-jacketed construction. The inner tank is typically stainless steel designed and tested consistent with the ASME pressure vessel code. The outer tank or "jacket" is typically carbon steel. The vacuum space is filled with a low-conductivity granular material such as Perlite or multi-layer insulation (MLI) to minimize both radiation and convection heat transfer. The inner tank has various pressure-relief devices (Figure 2-14) consistent with applicable codes. This includes pressure-relief valves backed up by rupture disks, which open to vent product to preclude over-pressuring the inner tank. There are usually two sets of these valve/disk combinations so that one set can be isolated (e.g., for valve testing or disk replacement). The outer vessel is not a pressure vessel, and so it is fitted with a relief device so that it vents if the inner tank leaks into the vacuum space. Two important specifications (in addition to capacity) affecting liquid hydrogen tanks are the maximum allowable working pressure (MAWP) and normal evaporation rate[6] (NER).

The hydrogen liquid and vapor phases in the storage tank are generally at or near saturation (i.e., equilibrium), and both the saturation pressure and temperature increase with time (if there is no venting) as heat leaks into the tank. The saturation pressure and temperature of the hydrogen delivered by the tank truck is relatively low because it is "fresh" from the liquefier. There are two possible strategies for using cryogenic liquid hydrogen tanks in a fueling station application. One strategy is to equip the tank with a pressure-regulator valve so that it vents to maintain a constant pressure less than the MAWP. The CaFCP station profiled in Appendix A uses this design. The other is to allow the tank pressure to increase from the relatively low level following tank-truck delivery up to the PRD setting (which is usually slightly less than the MAWP). If the station throughput is high enough and the delivery of fresh "cold" liquid hydrogen is frequent enough, then the storage tank pressure will never reach the PRD setting and no product will be lost due to venting.

A reciprocating rather than a centrifugal cryogenic pump must be used to pump the liquid hydrogen to the high pressures needed for compressed hydrogen dispensing. As previously discussed and illustrated in Figure 2-14, these pumps are simpler and require much less drive power than hydrogen gas compressors. A variety of pump designs are potentially applicable to hydrogen fueling stations, and most of the tradeoffs involve increased complexity to decrease the amount of hydrogen vaporized. The basic problem is that cryogenic pumps vaporize a substantial quantity of product in order to cool down and "prime," unless they are constantly submerged in liquid (which also exacerbates vaporization). Options for minimizing this vaporization include more expensive pumps with less suction head requirement, elevating the tank above the pump to increase the suction head, and use of a small sump-submerged centrifugal pump as an "inducer" for the high-pressure reciprocating pump. In all cases, the piping connecting the pump to the storage tank is vacuum jacketed as indicated in Figure 2-14. Companies that manufacture cryogenic hydrogen pumps and provide additional details

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[6] NER is usually expressed as a percent of the tank capacity that evaporates per day due to heat leaks. It is important to note if the NER is specified in terms of a gas other than hydrogen and the vent pressure associated with the NER specification.

in their literature include APCI (Reference 20), ACD (Reference 21), and Cryostar (Reference 22).

The heat exchanger used with this type of station (Figure 2-14) is often referred to as a vaporizer, even though the fluid is supercritical and no literal vaporization occurs. Figure 2-14 sketches how vaporizers rated for very high-pressure service must be used in the pump-and-warm design. Ambient-air vaporizers are adequate for stations with low throughput, but forced-air (i.e., with fans or blowers) may be needed for hydrogen fueling stations with higher throughput.

In designing a hydrogen fueling station of this type, there are important tradeoffs associated with the control system strategy and sizing of components. For example, if the high-pressure gas storage is a large-volume cascade, a relatively small-capacity pump can operate with few starts and stops. On the other hand, a high-capacity pump (which cycles on and off as vehicles are being refueled) can be used with a small-volume high-pressure gas buffer tank.

Because hydrogen-fueled vehicles are a nascent technology, there is not much field experience with hydrogen fueling stations to guide planning and design tradeoffs; however, the type of hydrogen fueling station addressed in this section, when configured as a pump-and-vaporize design (Figure 2-14), is identical to a liquid-to-compressed natural gas (L/CNG) fueling station with respect to the process flow. Large L/CNG stations have been built, and they operate successfully to routinely refuel fleet vehicles in every day service. For example, Figure 2-15 shows one of two L/CNG stations owned and operated by Omnitrans, which is a transit agency in the San Bernardino Valley area of California. These two stations dispense approximately 10,000 gallons of L/CNG (the energy equivalent of roughly 6,400 kg of hydrogen) into over 100 full-size CNG buses every day. Although the fact that hydrogen properties are different than natural gas properties will make the design of hydrogen stations more challenging then the design of L/CNG stations, the success of these L/CNG stations provides encouragement regarding the basic feasibility of the type of hydrogen fueling stations considered in this section.

LNG tank, pumps, vaporizer, and CNG tanks

Dispensing island

Figure 2-15. Omnitrans (San Bernardino) dispenses approximately 10,000 gallons/day of L/CNG into 100 transit buses from two stations that have the same basic process flow design as the hydrogen station illustrated in Figure 2-14.

2.3.2.3 On-Site Reforming

Technologies that enable the on-site production of hydrogen from natural gas or other hydrocarbon feedstocks are typically called reformers because they *reform* the hydrocarbons into carbon monoxide (CO) and hydrogen.

Figure 2-16 illustrates a simplified example of configuration for a hydrogen fueling station with an on-site reformer. The principal elements of the hydrogen production system are the natural gas and air supply, reformer, and purification system. The configuration details differ with each reforming option.
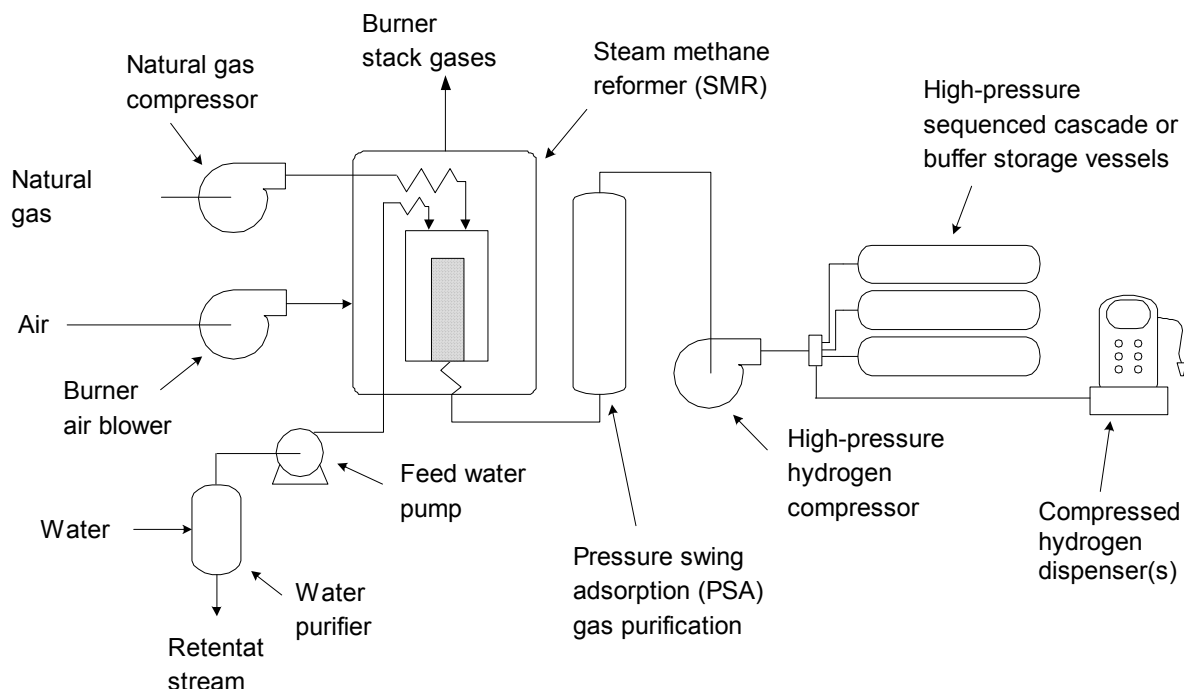
Figure 2-16. Simplified process flow schematic for a hydrogen fueling station with an on-site reformer

In general, hydrogen and other gases are produced in the reformer, a pressure swing adsorption system is used to purify the hydrogen product stream, and the purified hydrogen is compressed, stored in buffer or cascaded vessels, and dispersed to vehicles as discussed in previous sections. Several reformer technologies are already used commercially for hydrogen production (mostly for non-vehicle applications) and have near to long term potential for being available for refueling station on-site hydrogen production.

A challenge in using reformers for on-site hydrogen production is that most of these approaches have not been available as integrated systems at a scale appropriate for projected near-term hydrogen vehicle fueling requirements (approximately 20 to 1,000 kg/day). In addition, reformers are best operated under steady-state conditions and therefore require a relatively constant demand for hydrogen. The operator of a hydrogen fueling station will likely be dealing with custom engineering companies or system developers with evolving technology. On-site reforming does, however, offer the promise of relatively low cost hydrogen compared to other decentralized production methods (References 23 and 24).

Reformer Technologies

Three basic reformer technologies are potentially applicable to hydrogen production on-site at refueling stations: steam reforming (SR), partial oxidation (POX), and autothermal reforming (ATR). These technologies and their primary tradeoffs are summarized in Table 2-7 and more details are discussed in the following sections.

Table 2-7. Summary of hydrocarbon reforming processes

Method	Principle	Considerations
Steam Reforming (SR)	Reform methane using steam. $CH_4 + H_2O \rightarrow CO + 3H_2$ (Also applicable to methanol reforming)	Advantage: High purity product to ~75% (no nitrogen dilution). High efficiency. Disadvantage: Requires steam for initial operation making startup more complex. Requires sophisticated equipment design and high-grade metallurgies.
Partial Oxidation (POX)	Oxidation of CH_4 $CH_4 + \frac{1}{2} O_2 \rightarrow CO + 2H_2$	Advantage: Quicker start-up. No requirement for steam to POX reaction. Suitable for heavier hydrocarbons Disadvantage: Maximum of 2 hydrogen moles produced per mole of methane feed. Low purity product (~35%) making purification more difficult. Low efficiency.
Autothermal Reforming (ATR)	Combination of partial oxidation and steam reforming. $CH_4 + \frac{1}{2} O_2 \rightarrow CO + 2H_2$ $CH_4 + H_2O \rightarrow CO + 3H_2$	Advantage: Quicker start-up. Efficiently uses heat produced by partial combustion for endothermic steam reforming. Reformate product hydrogen can be as high as 55%. Material is near shift equilibrium at exit of reforming bed. No fired heater or higher grade metallurgies required.

These discussions focus on hydrogen production by methane reforming; however, methanol reforming is also discussed in the steam reforming section.

Steam Reforming

Hydrogen production is accomplished in several steps: a steam reforming step followed by a water gas shift reaction and hydrogen purification. This is the most well known and commercially available process for hydrogen production. In the United States, nearly 90 percent of the hydrogen is manufactured through the steam reformation of natural gas (Reference 25).

Steam reforming involves the reaction of natural gas (or other hydrocarbon feedstocks) with steam to produce CO and hydrogen. This reforming reaction is represented as:

$$CH_4 + H_2O \rightarrow CO + 3 H_2$$
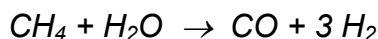
The steam reforming reaction requires external heat input. Economics favor reactor operation at pressures of 3 to 25 atmospheres and temperatures of 1,300 to 1,550°F. The external heat needed to drive the reaction is often provided by the combustion of waste gases, such as combustion of the purge gas from the hydrogen purification system.

Further processing of the gas stream with steam in a shift reactor produces CO_2 and additional hydrogen: $CO + H_2O \rightarrow CO_2 + H_2$

The gas exiting the shift reactor contains mostly H_2 (70 to 80 percent) plus CO_2, CH_4, H_2O and small quantities of CO. Depending on the type of shift reactor, CO concentrations are a few percent by volume or less. Hydrogen is then purified, typically by pressure swing adsorption (PSA) systems, although palladium membranes or other technologies are also options. The product hydrogen can have a purity of up to 99.999 percent. A purity of 98 percent hydrogen is specified in ISO 14687 for fuel cells for transportation and stationary applications. Compared with other reforming approaches, a high temperature steam reformer with methane feedgas can be expected to produce the greatest amount of hydrogen per unit of natural gas. The energy conversion efficiency[7] of large-scale steam methane reformers is between 75 and 80 percent, although 85 percent efficiencies have been achieved with additional waste heat recovery and utilization (References 26 and 27).

For large-scale chemical processes such as oil refining, steam reformers produce 25 to 100 million standard cubic feet of hydrogen per day (59,000 to 240,000 kg/day). These systems consist of long (12 meter) catalyst-filled tubes, operating at temperatures of 1,550°F and pressures of 15 to 25 atm, necessitating the use of expensive alloy steels. Refinery type (high-pressure, high temperature) long-tube reformers can be scaled down to as small as 0.1 million scf/day (240 kg/day) of hydrogen production. Small-scale conventional (long-tube, high-temperature) steam methane reformers are commercially available from a number of companies that normally produce large steam methane reformers for chemical and oil industries. The main design constraints for these systems are high throughput, high reliability and high purity (depending on the application). The disadvantages of conventional long-tube steam reformers for hydrogen refueling station applications are their large size, high material costs (for high temperature, high pressure operation), and high engineering/installation costs (for these one-of-a-kind units). For these reasons, it is generally believed in the hydrogen and fuel cell R&D communities that a more compact, lower cost reformer will be needed for on-site hydrogen production at refueling stations (References 25, 28, and 29).

Reformer development work is progressing toward this goal. For example, a number of companies have developed steam methane reformers that reform natural gas to produce reformate (hydrogen, CO, and CO_2 mixtures) for closely coupled fuel cells

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[7] Efficiency is defined here as hydrogen product (HHV)/feedstock energy input (HHV). Efficiency is also sometimes defined as hydrogen product (HHV)/feedstock energy input (HHV) + electric input, and this is sometimes defined in terms of LHV instead of HHV.

designed to operate with these mixtures. These include APCI, Haldor Topsoe, International Fuel Cells (IFC), Ballard Power Systems, Hydrogenics, Pan American, Sanyo Electric, and Osaka Gas Company. Praxair, in a joint venture with IFC, has recently commercialized a small stand-alone hydrogen production system based on this type of reformer (Reference 30). Harvest Energy Technology, Dais-Analytic Corporation, IdaTech, and H2Gen are working on small-scale systems.

Hydrogen can also be produced from hydrocarbons other than methane using the steam reforming process. Methanol is of particular interest. Because it can be stored like gasoline, and because it can be reformed to produce hydrogen, methanol has been proposed as a fuel for fuel cell vehicles. Experimental fuel cell vehicles with onboard methanol reformers have been demonstrated by DaimlerChrysler, Toyota and Nissan. In addition, small hydrogen production systems based on methanol reforming are in commercial use. Although these technologies are being developed for fuel processors on fuel cell vehicles, it has also been suggested that hydrogen might be produced by steam reforming methanol at refueling stations (Reference 31).

Because of its chemical composition, methanol is readily steam reformed at moderate temperatures. The overall reaction for hydrogen production via methanol steam reforming is:

$$CH_3OH + H_2O \rightarrow CO_2 + 3H_2$$
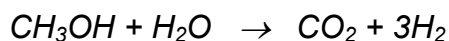
The reaction takes place in the presence of copper/zinc catalysts in the temperature range of 400 to 660°F.

Since the temperature of methanol steam reforming is much lower than that of a conventional (high temperature) steam reformer, the system may offer advantages in terms of capital cost, complexity, and energy requirements for start up. The tradeoff is that methanol is typically a more costly feedstock than natural gas (on a $/MMBtu basis).

Partial Oxidation

Partial oxidation uses oxygen (as either oxygen in air or pure oxygen) to partially combust hydrocarbon fuels to carbon monoxide and hydrogen. Methane (or some other hydrocarbon feedstock) is oxidized to produce carbon monoxide and hydrogen according to:

$$CH_4 + 1/2O_2 \rightarrow CO + 2H_2$$
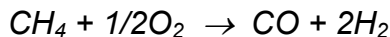
The hydrogen content of the product reformate from partial oxidation systems are 30 to 33 percent (dry). The balance is carbon dioxide and nitrogen, making purification by pressure swing adsorption with reasonable recovery difficult.

Catalysts are not required because of the high temperature; however, the hydrogen yield per mole of methane input (and the system efficiency) can be significantly

enhanced by use of catalysts (References 32 and 33). A hydrogen plant based on partial oxidation includes a partial oxidation reactor, followed by a shift reactor and hydrogen purification equipment. Large-scale partial oxidation systems have been used commercially to produce hydrogen from hydrocarbons such as residual oil for applications such as refineries. Large systems generally incorporate an oxygen plant, since operation with pure oxygen rather than air reduces the size and cost of the reactors.

Because they are more compact and do not require indirect heat exchange (as in steam reforming), some developers and researchers have argued that partial oxidation systems (and ATRs, to be discussed subsequently) could have a lower capital cost than steam reformers. Although the partial oxidation reactor is likely to be less expensive than a steam reformer vessel, the downstream shift and purification stages are likely to be more expensive (Reference 25). Limited operating data suggests a hydrogen production efficiency of 50 percent from POX systems (Reference 33) with higher efficiencies being possible for ATR systems. Hydrogen Burner Technology (HBT) manufactured POX prototypes in the 1990s that produced 20 and 200 kg/day of hydrogen. These systems were designed to operate with PSA purification systems.

Autothermal Reforming

Autothermal reforming uses a partial oxidation step followed directly by steam reforming, generally in the same vessel. The steam required for the steam reforming step can be passed through the partial oxidation bed to decrease the peak temperature experienced. Chemical reactions are as follows:

$$CH_4 + H_2O \;\rightarrow\; CO + 3H_2$$

$$CH_4 + 1/2\,O_2 \;\rightarrow\; CO + 2H_2$$
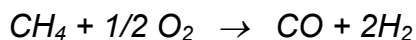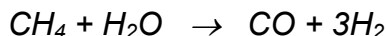
When using atmospheric air, every mole of O_2 results in 3.76 moles N_2 in ATR product, which must be subsequently removed from the product stream.

This system makes use of the heat produced in the exothermic oxidation reaction by passing it directly to the steam reforming bed. This means that no fired heater or expensive metallurgy is required to transfer that heat to the process stream for reforming. Relative to the partial oxidation process, less air is required because not all the methane conversion takes place in the partial oxidation section of the plant. Unconverted methane passing from the partial oxidation zone is further converted in the steam reforming section of the process. The cost of the process equipment is less than steam reforming because peak temperatures in this process do not require special metallurgy.

The reformate product hydrogen purity from an ATR process can be as high as the 50 to 55 percent. The improvement over POX is due to the more efficient conversion of methane in the steam reforming bed. An advantage of the system is that the heat used to promote the reforming reaction is produced in-situ. This simplifies the equipment

design required to provide sufficient heat to the reforming bed. With higher product purity than POX, the PSA purification step can be more efficient, providing hydrogen recovery in the range of 70 percent.

ATRs with capacities of 5 to 10 kg per hour will be available commercially in 2003 from Hyradix, a Division of U.O.P. Intensive on-going R&D projects include ChevronTexaco, H2Fuel, HydrogenSource, McDermott Technology Inc, Nuvera, and others.

On-Site Reformer Hydrogen Fueling Station System Description

The requirements for a hydrogen fueling station with a reformer depend on factors such as equipment count and size, utility hookups, and code requirements. Figure 2-16 illustrated the principal elements of such a station with a steam reformer and PSA purifier. Several subsystems make up the reformer. These include the reformer itself, heat exchangers for preheating and steam supply, shift reactors, and the purification system, natural gas, air, and water supplies.

Two important factors pertaining to this type of station are the supply pressure of natural gas and the output pressure from the reformer. Steam reformers can be designed to operate at near ambient pressure or as high as 10 atm (150 psig). A higher pressure reformer can provide high pressure reformate gas to the purification system and eliminate the need for an intermediate reformate compressor. While this detail would appear to be more important for the reformer developer, it can affect the natural gas pressure requirement for the reformer system. Station planning and design must consider the capital and operating costs associated with natural gas and hydrogen compression requirements and tradeoffs.

Packaging and integration varies greatly among reforming systems. Most current generation systems are containerized for easy shipping and quick installation. Field assembly is or will be limited to providing utilities and anchoring the reformer container at the customer's facility. Examples of reformer systems include the Air Products steam methane reformer recently installed at the City of Las Vegas and the unit being developed by Hyradix for SunLine.

Similar compact designs include a steam reformer system under development by H2Gen (Figure 2-17). This system is intended to require only natural gas, electric and water hookups, with pure hydrogen exiting the system. Low-pressure hydrogen would be produced, which would require compression, storage, and a dispenser for vehicle fueling. A fully integrated system is intended to integrate code and safety requirements (Reference 34).

Smaller integrated ATRs are also under development. These "5kW" ATRs have a footprint of approximately 3 ft x 3 ft. Examples are shown in Figure 2-18. They are designed to produce reformate gas mixtures for fuel cells. These gas streams could also be purified to produce hydrogen.

Section 3 discusses the code and installation requirements for hydrogen equipment. Key considerations are codes for boilers and pressure vessels and equipment containing flammable gases. Locations of vents and distances from ignition sources are among the parameters that need to be specified.

Figure 2-17.   H2Gen Steam Reformer System; hydrogen production capacity is about 25 kg/day.

Figure 2-18. Chevron Texaco Halias and Hydrogen Source integrated ATRs provide hydrogen for fuel cells (approximately 5 kg/day). These systems do not include purification.

Utility Requirements

The principal utility requirements for a stream reformer system are natural gas, water, and electric power. The availability of these utilities (and the natural gas supply pressure) is an important factor affecting any consideration of a hydrogen fueling station with an on-site reformer.

Utility requirements depend on system capacity and configuration, and they are typically described by reformer efficiency expressed as the hydrogen energy output divided by the feedgas plus electric energy input.

Several studies (References 23, 24, 33, and 35) project the efficiencies and energy requirements for steam reformers that might be used on-site at a hydrogen fueling station. Near-term efficiencies are likely to be 65 to 70 percent (on an LHV basis). Table 2-8 shows estimated utility requirements for an example 240 kg/day natural gas steam reformer system. The performance parameters are intended to illustrate the extent of utility requirements and not specify system performance.

Table 2-8. Example Utility Requirements for Steam Reformer System

Parameter	Approximate Requirement
Hydrogen capacity	240 kg/day, 10 kg/hr
Natural gas flowrate	1700 scfh
Water consumption	10 gal/hr
Reformer system power	7.6 kVA, 35 A, 220 V
Compressor system power	30 kVA, 70 A, 440 V

2.3.2.4 On-Site Electrolysis

Electrolysis is another option for on-site production of hydrogen at a refueling station. Electrolysis uses only water and electricity as inputs and has the potential for producing hydrogen from non-fossil sources with zero emissions. Several companies have built electrolysis-based hydrogen production systems with a range of production capacities for both industrial and vehicle fueling applications.

The advantages of electrolysis in the near term include its replacement of the need to store large quantities of liquid or high-pressure gaseous hydrogen on-site at the station, its suitability for smaller scale production, and zero emission operation. No truck traffic or air emissions would be associated with an electrolyzer-based facility. Electrolyzers are considered a reliable, well-developed option compared with other on-site production approaches. One drawback of electrolysis is the cost of electricity combined with the low ratio of hydrogen production to electricity consumption. Also, compared to stations with compressed or liquid hydrogen storage which are well suited to either fast-fill or time-fill applications, stations with electrolyzers are best suited to time-fill operations. This is because electrolyzer economics favor near-continuous operation, and fast-fill applications require either intermittent operation of a large-capacity electrolyzer or large-capacity compressed hydrogen storage vessels.

Electrolyzers can operate at elevated pressures to produce hydrogen at pressures ranging from atmospheric to 1,800 psig, with 3,000 psig units under development. The higher output pressure reduces the downstream compression energy requirement and capital cost of the compressor. Some additional compression will be required for automotive applications, particularly for fueling at 5,000 psig.

Operating Principles and Electrolyzer Types

Electrolysis is the process of splitting water into hydrogen and oxygen with electricity by transmitting an electrical current through an electrolyte. Oxygen and hydrogen gases are produced at the anode and the cathode respectively, separated from the electrolyte, and gathered in separate vessels for further processing. The anode is the electrode through which the electrons leave the electrolytic cell and produce gaseous oxygen.

Similarly, the cathode is the electrode where electrons enter the electrolytic cell and produce gaseous hydrogen.

Figure 2-19 illustrates the basic water electrolysis process and the key energy balance considerations. The energy quantities are for the production of one mole of hydrogen at 25°C (77°F) and one bar (approximately one atmosphere). The ideal electric energy requirement is the change in the Gibbs function (which is noted as ΔG in
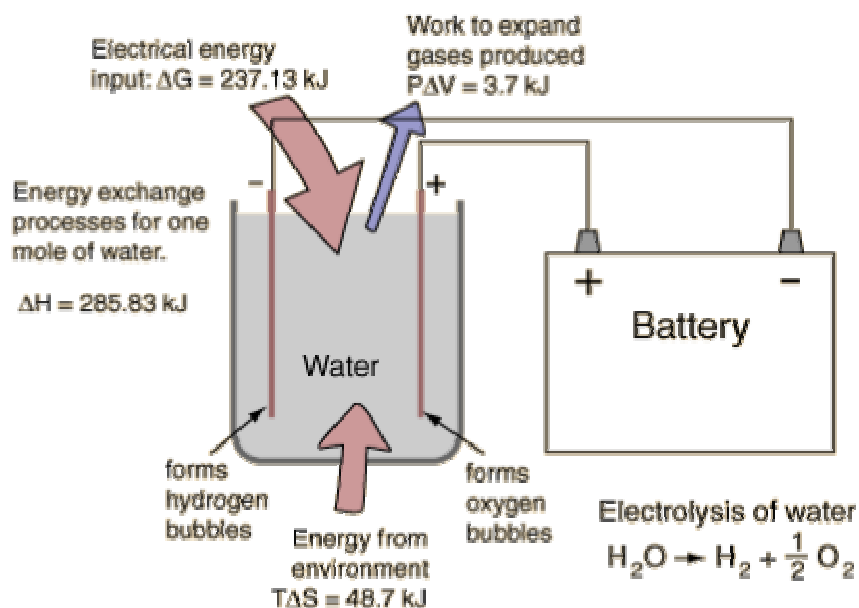
Figure 2-19. Basic Water Electrolysis

Figure 2-19), and this is equal to the reaction enthalpy (ΔH) minus the product of the temperature and reaction entropy ($T\Delta S$):

$$\Delta G = \Delta H - T\Delta S$$

This illustrates that the electric energy requirement decreases (and the hydrogen-production efficiency increases) when electrolysis cells are operated at higher temperatures. While this is generally true (and therefore high-temperature electrolysis is the subject of current R&D), many other factors (such as excess cell voltage effects) are also involved.

The electric power required to produce a given hydrogen output flow can be calculated from these thermodynamic energy balance considerations. For hydrogen fueling station applications, the electrolyzer efficiency is often defined as the hydrogen output LHV divided by the input electrical energy. A 100 percent efficiency electrolyzer would therefore require approximately 33 kW-hr per kg of hydrogen production. Real electrolyzer efficiencies can range from approximately 60 to 90 percent, depending on

various design and operating details; however, it is clear that the overall efficiency of producing hydrogen using a reformer is superior to using the hydrocarbon feedgas to generate electricity to power an electrolyzer. This is why nearly all large-scale hydrogen production in the U.S. is done by reforming, and large-scale production by electrolysis is used primarily in areas with low-cost electricity (e.g., due to hydro generating resources).

At existing hydrogen fueling stations with on-site electrolyzers, most of the electricity to power the electrolyzer is usually obtained from the utility grid, and this electricity is typically produced in power plants using fossil fuels. Yet, it may also be produced from renewable sources like solar and wind energy as well as hydro and nuclear power. Hydrogen fueling stations at SunLine Transit and American Honda utilize solar photovoltaic panels to provide part of their electrolyzer power. The Figure 2-20 illustrates a generic electrolyzer-based hydrogen fueling station that includes water and electricity supply, purification system, and electrolysis unit.

Alkaline and solid polymer electrolyte (SPE) membrane electrolyzers are the two most common types used for hydrogen production. These two technology options differ in their cost (operating and capital), reliability, and efficiency.

Alkaline Electrolysis

Alkaline is the oldest electrolysis technology and the one typically used for large-scale electrolytic hydrogen production. Diluted potassium hydroxide (KOH) or sodium hydroxide (NaOH) are normally used as the electrolytes. The anode and cathode reactions are:

$$2\ OH^- \ \rightarrow \ 1/2\ O_2 + H_2O + 2e^- \qquad \textit{at the anode}$$

$$2\ H_2O + 2e^- \ \rightarrow \ H_2 + 2\ OH^- \qquad \textit{at the cathode}$$
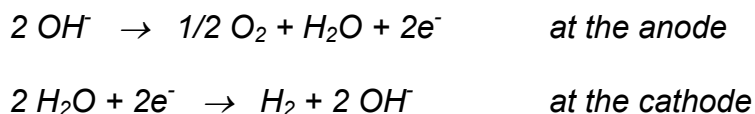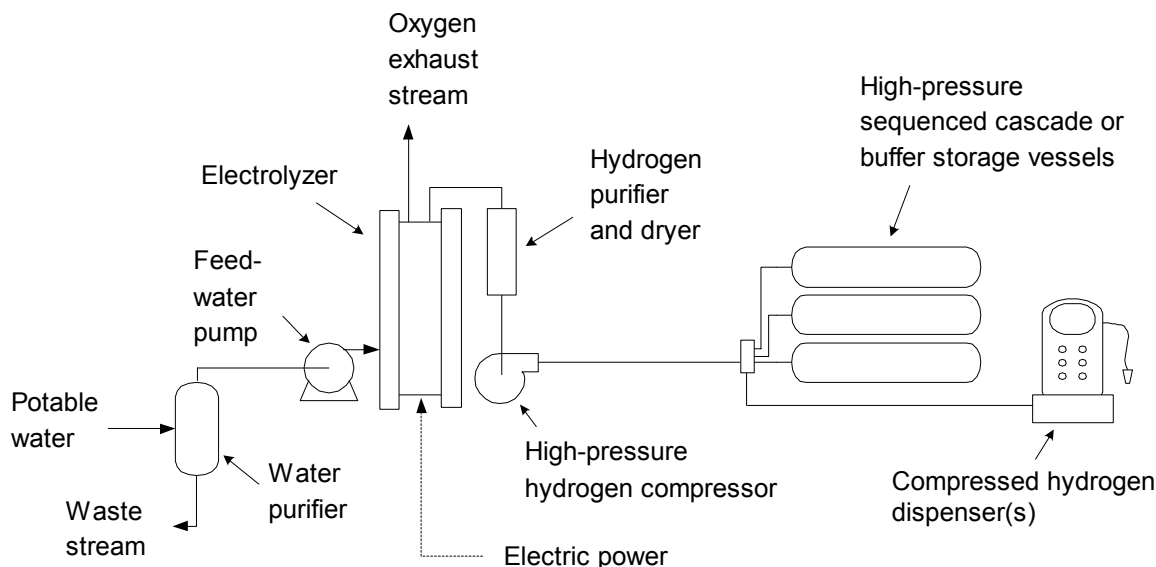
Figure 2-20. Simplified process flow schematic for a hydrogen fueling station with an on-site electrolyzer

Norsk-Hydro built one of the first large-scale water electrolyzers in 1927, with the hydrogen serving as feedstock for ammonia production (Reference 36). These units operate near ambient pressures and at temperatures in the 160 to 180°F range and typically have electrical efficiencies of 60 to 80 percent. Alkaline electrolyzers have been developed to operate at higher pressures and/or higher temperatures. High-temperature alkaline electrolyzers have higher electrical efficiencies (as high as 90 percent, because of various factors including the improved reaction kinetics at the electrodes, which increases the current density), but these designs present more durability-affecting materials challenges.

The principal components of an alkaline electrolyzer system for hydrogen production are:

- Cells and electrodes — Alkaline electrolyzers require the use of gas separators between the electrodes to prevent the migration of hydrogen to the oxygen side and vice versa. Key characteristics for gas separators are low gas permeability, low ohmic resistance, high mechanical strength, and long life in a corrosive environment. The electrodes must be able to withstand highly corrosive environments, be highly conductive, and have high surface activity. Hence, the electrodes are typically porous with nickel-based catalysts.

- Water purification — Demineralizers, reverse-osmosis units, and/or carbon filter cartridges produce the high-purity water required by electrolyzers.

- Gas generation system, seals, and electrolyte handling — Components that are part of these systems include: conductivity sensor, leak detector, feed water bowl level sensor, feed pumps, cell stack temperature and water level control, ventilation blower, water seals, demisters, hydrogen ballast and hydrogen gas analyzer, and a deoxydizer.

- Hydrogen purification and dryer system — A twin-bed regenerative molecular sieve dryer, coalescing filters, and carbon adsorbtion filters are typical components used to dry and purify hydrogen intended to be used as a fuel cell vehicle fuel.

Additional components are required to compress, store, and dispense the hydrogen when the alkaline electrolyzer is part of a hydrogen fueling station. These components are identical to the ones previously discussed in Section 2.3.1 and 2.3.2.1.

Solid Polymer Electrolyte (SPE) Membrane Electrolysis

Solid polymer electrolyte (SPE) membrane electrolyzers operate as reverse proton exchange membrane (PEM) fuel cells, and they typically use similar parts and materials. In SPE electrolyzers, a solid-state ion-conducting membrane (the SPE) replaces the liquid electrolyte used in alkaline electrolyzers. The anode and cathode reactions are:

$$2\,H_2O \;\rightarrow\; O_2 + 4\,H^+ + 4e^- \qquad \textit{at the anode}$$

$$2\,H^+ + 2e^- \;\rightarrow\; H_2 \qquad\qquad \textit{at the cathode}$$
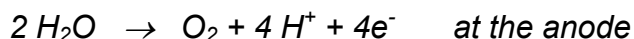
PEMs were first developed for the chlor-alkali industry. These specialized materials are solid fluoropolymers, which have been chemically altered to make them electrically conductive. The polymers typically used in these devices are perfluorocarbon sulfonates. One common type is polyfluorotetraethylene (PFTE), commonly referred to as Nafion®, which is the membrane material used in some PEM fuel cells. The fluorocarbon chain or backbone consists of many repeating structural units. Treatments like *sulphonation* or *carboxylation* insert ionic or electrically-charged pendant groups, statistically spaced, into some of these base units to provide the properties most suited for the application.

Because of the low internal resistance of SPE membrane assemblies, they can operate at higher efficiencies than alkaline electrolyzers. Efficiencies of 90 percent have been reported in SPE electrolyzers in Japan, and a demonstration unit is being installed in Takamatsu, Japan (Reference 37). These units typically operate at pressures from 100 to 300 psig and at temperatures between 200 and 250ºF. While SPE electrolyzers have the potential for high efficiency, the actual efficiency depends on the load factor. Higher loads result in more power consumption, but they also increase the hydrogen output. Similar load versus efficiency tradeoffs are exhibited with PEM fuel cells, batteries, and other electrochemical devices.

SPE electrolyzers require components similar to alkaline electrolyzers for hydrogen processing prior to compression, storage, and dispensing for fueling station applications.

Other Types of Electrolysis

Consistent with the electrolyzer thermodynamics summarized in Figure 2-19, the electrolyzer electric power consumption can be reduced if part of the energy required for water decomposition is supplied by high-temperature heat. This has been the motivation for high-temperature steam electrolysis research, which was initiated over twenty years ago (Reference 38) and is currently underway at the Lawrence Livermore National Laboratory and the Idaho National Engineering and Environmental Laboratory.

Commercial Electrolyzer Availability and Applications

Companies currently manufacturing electrolyzers include Stuart Energy Systems, Van Den Borre Hydrogen Systems (recently purchased by Stuart Energy), Proton Energy, Norsk Hydro, Teledyne Energy Systems, and Hamilton Sundstrand.

Figure 2-21 shows a Stuart Energy elecrolyzer installed at the SunLine Transit hydrogen fueling station, and Figure 2-22 shows a Proton Energy electrolyzer.

Figure 2-21.   Example: Stuart Energy Electrolyzer Installation at the SunLine Transit Hydrogen Fueling Station

Figure 2-22. Proton Energy Electrolyzer

Several hydrogen fueling stations with on-site electrolyzers have been installed in North America. As of March 2002, these include the following:

- The California Fuel Cell Partnership satellite station at the AC Transit bus yard in Richmond, CA
- American Honda Motors, Torrance, CA
- SunLine Transit Agency in Thousand Palms, CA
- Toyota Motor Company, Torrance, CA
- City of Chula Vista, Chula Vista, CA
- Arizona Public Service, Phoenix, AZ
- Ford Motor Company, Romeo, MI
- Ford Motor Company vehicle testing center, Phoenix, AZ
- Power Tech Laboratories, Vancouver, B.C.
- Stuart Energy Systems, Toronto, Ontario

Utility Requirements

The principal utility requirements for electrolyzers are water and electric power. These utility requirements depend on the hydrogen fueling station dispensing capacity

requirement and the type of electrolyzer used. The performance and efficiency of an electrolyzer varies with each manufacturer and model, depending on the specific technology and configuration. An electrolyzer, which is 75 percent efficient (LHV basis), would require 44 kWh/kg of hydrogen for electrolysis and roughly 4 kWh/kg for compression (depending upon the electrolyzer output pressure).

The site will require a constant supply of water. Standard city-grade potable water is an acceptable feedstock to a demineralizer water purification system. Inert gases such as nitrogen are also needed for start-up and maintenance modes.

Table 2-9 shows estimated utility requirements for an example of a 72 kg/day on-site electrolyzer system. The performance parameters are based on the estimates discussed above. Table 2-9 illustrates that substantial electric power service is required for a station with an on-site electrolyzer and this may require electric utility upgrades at some facilities.

Table 2-9. Example: Utility Requirements for an Electrolysis System

Parameter	Approximate Requirement
Hydrogen Capacity	72 kg/day, 3 kg/hr
Water consumption	8 U.S.gal/hr
Electrolyzer system power	500 amp service at 480 volts
Compressor system power	50 hp

2.3.2.5 Mobile Hydrogen Fueling Units

Fueling facilities in general and hydrogen fueling facilities in particular can be permanent installations, skid-mounted, portable, mobile, or wet-hosing units. These terms do not always have precise and universally agreed-on definitions; however, the implications of a permanent fueling station are reasonably clear and a mobile fueling station is defined here as a wheeled unit (either towed or driven) that is fully self-contained. It does not "hook up" to a compressor or dispenser; it has its own dispenser and perhaps compressor. It remains on wheels while it is being used, and it may be replaced (e.g., after it has been depleted of usable hydrogen) with frequencies ranging from hours to months. Wet-hosing (a term applied most often to diesel or aircraft equipment fueling) refers to a mobile fueling unit that travels to the equipment being refueled instead of the equipment traveling to the parked refueling unit. This section discusses mobile fueling units for hydrogen-fueled vehicles.

Figure 2-23 sketches one example concept for a mobile hydrogen unit. This trailer (or it could be a truck) consists of some number of compressed hydrogen vessels, control and metering equipment, a dispenser with a hose and nozzle, and appropriate safety systems. The compressed hydrogen vessels would most logically be arranged as a

priority-sequenced cascade (as discussed in Section 2.3.1.2 and 2.3.2.1) in order to increase the storage efficiency (i.e., to maximize the number of vehicles that could be
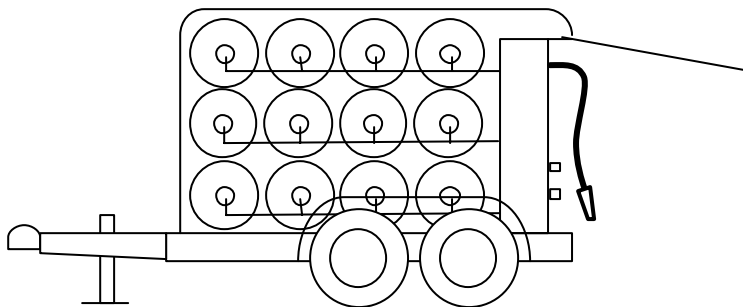
Figure 2-23.   Example: Mobile Hydrogen Fueling Unit Concept with Compressed Hydrogen Storage and Dispensing

refueled before this type of mobile fueling unit had to be refilled). Much higher storage efficiencies can be obtained if the mobile fueling unit includes a compressor and buffer storage tanks. These options involve tradeoffs of equipment complexity and cost, storage vessel volumes and configurations, compressor capacities, dispensing rates, and total dispensable hydrogen quantity (before the unit must be refilled).

Another mobile hydrogen fueler configuration possibility is a truck- or trailer-mounted vacuum-jacketed liquid storage tank, pump, vaporizer, buffer tank, and dispenser. Such a system could store substantially more hydrogen than high-pressure gas vessels. While mobile LNG fueling units are in current use (Reference 39), no mobile fueling units that store the hydrogen as a liquid are known to exist.

A different type of mobile hydrogen fueling unit concept produces hydrogen using an on-board electrolyzer or reformer. Such units require connection to water or natural gas (and electric) supplies, and they must also include compression, storage, and dispensing equipment. Mobile hydrogen fueling units with small electorlyzers have been built and demonstrated, but no mobile units with reformers are known.

Table 2-10 lists some specific mobile hydrogen fueling units that have been announced by various companies. The table indicates the company, their designation of the unit, what type it is, a brief description, and remarks regarding the status. Table 2-10 lists one unit (the Quantum Compact Hydrogen Refueler) that requires connection to a hydrogen supply, and it also lists mobile hydrogen fueler components announced by FuelMaker, neither of which precisely meets our mobile hydrogen fueling unit definition. Furthermore, the units listed range from commercially available products that have been demonstrated to concepts that have been announced. Planners interested in mobile hydrogen fueling units should check to determine the latest status and potential new offerings.

The APCI Mobile Hydrogen Fueling Unit and Quantum HyHauler^{TM} concept store hydrogen gas in high-pressure vessels and have integrated dispensing equipment. Figure 2-24 shows an artist's rendering of the APCI Mobile Hydrogen Fueling Unit.

Table 2-10. Specific mobile hydrogen fueling equipment that has been announced

Company	Product	References	Type of Device	Description	Remarks
Air Products and Chemicals	Mobile Hydrogen Fueling Unit	Press release 12/10/02, APCI product datasheet	Trailer-mounted integrated pressure vessels, dispenser, and controls	PLC-controlled priority-sequenced pressure vessel cascade. 162 kg total and up to 120 kg usable hydrogen capacity. 3,600 or 5,000 psi. SAE J2600 and CaFCP vehicle interface and controls. Monitoring telemetry. No utility connections required.	Demonstrated and available as a commercial product for sale or lease.
Quartum Technologies	Compact Hydrogen Refueler	Press release 1/7/03, Quantum technical literature	Small intensifier and dispenser unit on castors draws hydrogen from separate source	5,000 and 10,000 psi dispensing capability. CaFCP interface and various safety features. 10 kW, 480 V, 3-phase electric service required. Can be used with Quantum TriPak^{TM} pressure vessel cascade.	Demonstration and commercialization status unknown.
Quantum Technologies	HyHauler^{TM}	Press release 1/7/03, Quantum technical literature	Trailer-mounted hydrogen fueling station with storage cascade, compressor, and dispenser. Optional integrated electrolyzer	Various HyHauler^{TM} options include: TriPak^{TM} pressure vessel cascade provide 50 or 100 kg hydrogen storage. Compressor can accept hydrogen from external sources to boost cascade pressure. Dispensing at 5,000 psi or (with optimal booster) 10,000 psi. Utility requirements same as Compact Hydrogen Refueler. Can include integrated electrolyzer for hydrogen generation	Demonstration and commercialization status unknown.
Stuart Energy	Personal Fuel Appliance^{TM}	Stuart brochure and www.stuartenergy.com	Smaller electrolyzer, compressor, and dispenser on castors	Includes Double Electrode Plate® electrolyzer, compressor, hose, and nozzle. Operates from 240 V electric supply and "garden hose." Hydrogen production/dispensing rate not specified.	Prototypes used to refuel Ford, Honda, and Daimler Chrysler fuel cell vehicle exhibits. Not yet released as commercial product.
Stuart Energy	Trailer-installed Community Fueler	www.stuartenergy.com	Trailer-mounted electrolyzer, compressor, dispenser, and controls	System includes Stuart CF 1350 3-kg/hr electrolyzer, compressor, 60 kg of storage at 6,000 psi, 3-level cascade controller, 2-hose dispenser (3,600 and 5,000 psi) with CaFCP vehicle interface and controls. 500 A, 480 V, 3-phase electric service and water supply required.	Unit has been delivered to the City of Chula Vista
FuelMaker	Hydrogen Vehicle Refueling Appliance (HRA)	www.fuelmaker.com	Adapting CNG VRA to hydrogen applications	"The VRA components may be combined with an electrolyzer or reformer into a single integrated appliance which can be used to fuel a fuel cell vehicle directly."	FuelMaker literature indicates that their compressor, dryer, and controls are used in the Stuart Personal Fuel Appliance.

Figure 2-24. Air Products and Chemicals Mobile Hydrogen Fueling Unit

When the storage pressure drops to the minimum level for refueling, the unit is transported to a large-capacity high-pressure hydrogen source where it is refilled, and then it is transported back to the vehicle refueling site. "Full" units can be exchanged for "empty" units to maintain a constant refueling capability. The APCI unit offers condition monitoring via telemetry to automate replacement scheduling.

The Stuart Personal Fueling Appliance™ does not require periodic replacement because its on-board electrolyzer generates hydrogen, but it does require 240-volt electric service as well as a water supply. As noted in Table 2-4, a Stuart Community Fueler electrolyzer-based hydrogen fueling station is available installed in a trailer to provide a larger-capacity mobile unit. This system includes Stuart's three kg/hr Model CF 1350 electrolyzer together with a compressor, cascade storage vessels, dispenser, and safety systems. A trailer-installed Stuart Community Fueler has been delivered to the City of Chula Vista to support their hydrogen bus and automobile project (Figure 2-25).

While quantitative performance test data for mobile hydrogen fueling units are not yet available, it is clear that units with a substantial volume of high-pressure hydrogen should be able to provide a fast-fill capability until the hydrogen storage is depleted to a given level. On the other hand, units with electrolyzers (or reformers) do not need to be replaced, but they are limited to slow-filling unless they are also equipped with significant volume buffer or cascade storage vessels.

Photograph courtesy Stuart Energy

Figure 2-25. Stuart Trailer-installed Elecrolyzer "Community Fueler" delivered to Chula Vista

Section 2.2.2 discusses the potential advantages and applicability of mobile hydrogen fueling units. They may be well suited for hydrogen vehicle fleets with very low kg/day consumption or with growth projections too uncertain to support permanent station planning. Mobile units can also be used to provide temporary fueling while a permanent station is being installed. The most common application of mobile hydrogen fueling units to date has been to support fuel cell vehicle exhibitions and demonstrations at locations with no hydrogen fueling stations. While mobile hydrogen fueling units are well suited to many situations, permanent stations have lower lifecycle costs for established fleets with substantial kg/day hydrogen consumption.

Planners should be alert to issues associated with permitting and/or code-compliant use of mobile hydrogen fuelers, particularly in California. Prior applications of mobile CNG, LNG, and hydrogen fuelers have encountered delays in this regard. As discussed in Section 3.1, there is substantial uncertainty associated with codes and standards applicable to mobile hydrogen fueling units that are "parked" at a site and used to refuel vehicles. These uncertainties relate to the applicable pressure vessel codes, separation distances, and leak detection and fire suppression requirements. Planners should check with state and local authorities regarding the latest status of regulations affecting mobile hydrogen fueling unit applications.

2.3.2.6 Stations that Dispense Liquid Hydrogen

There are very few hydrogen fueling stations in the U.S. that dispense liquid hydrogen, and two of these are in California: the CaFCP station in West Sacramento and the BMW station in Oxnard (both of which are profiled in the appendix). These stations utilize liquid hydrogen dispensing technology that was developed in Germany, which is briefly described in this section.

Liquid hydrogen fueled vehicles and refueling station technology has been under development in the U.S., Germany, Japan, and elsewhere since the early 1970s (Reference 40). Nearly all of this development, until recently, has been directed toward hydrogen-fueled vehicles with internal combustion engines. The most substantial development work was carried out during the 1980s and 1990s in Germany. German companies and institutions included BMW, Linde, Messer Griesheim, Solar-Wasserstoff-Bayera (SWB), DFVLR (the German Aerospace Research Establishment, which has been renamed DLR), and others (References 41 and 42). Linde has continued this development through the present time (Reference 43), and liquid hydrogen dispensing stations in the U.S. utilize Linde technology and equipment.

There are unique challenges associated with the dispensing of liquid hydrogen into motor vehicles. Some of these challenges and the technology that has been developed to address them are summarized below.

- Boil off — As refueling is initiated, the flowing liquid hydrogen cools down certain station and vehicle fuel system plumbing from ambient to cryogenic temperatures. This vaporizes some of the liquid hydrogen, and the quantity of vapor generated is relatively high because of hydrogen's low heat-of-vaporization (e.g., compared to LNG). This challenge has been addressed by systems that re-circulate hydrogen vapor back to the station during the cool-down cycle, vacuum-jacketing all possible plumbing elements, and designing special nozzle-receptacle couplings (which are discussed subsequently).

- Contamination and Condensation — All plumbing involved in the refueling process that is exposed to the ambient environment must be thoroughly purged of air and moisture (that would freeze) before the refueling process starts. This is accomplished by evacuating and/or purging the lines with helium.

- Safety — Current liquid hydrogen dispensing systems incorporate safety features such as automatically performing a brief leak check prior to enabling the flow of liquid hydrogen. Their design essentially eliminates the possibility of air condensation, which would create a potentially dangerous oxygen-enriched environment. Minimal hydrogen escapes from the coupling as it is disconnected from the vehicle.

Figure 2-26 is a photograph of a recent-generation Linde liquid hydrogen refueling coupling (also called a nozzle) that connects to the vehicle receptacle. It is a positive-locking dry-break type coupling with vacuum-jacketed concentric liquid and vapor flow passages. Liquid hydrogen flows in the center tube, cold vapor is returned through the surrounding annulus, and both flow paths are vacuum jacketed. When the coupling is connected to the vehicle receptacle, an automatic sequence starts that includes: the opening of valves in the coupling and receptacle, projection of the inner tube (which Linde refers to as the "cold finger") into the receptacle, helium gas purge, leak check (by monitoring pressure decay), initiating liquid hydrogen flow while returning vapor during cool down, filling the vehicle tank with liquid hydrogen, and completing a pre-disconnect refueling termination sequence. Reference 43 provides additional details regarding the Linde coupling design.

Figure 2-26.   The Linde liquid hydrogen refueling coupling is used at the CaFCP West Sacramento and BMW Oxnard stations.

Liquid hydrogen dispensing stations store liquid hydrogen in a vacuum-insulated cryogenic vessel, which is exactly the same type as discussed in Section 2.3.2.2 and illustrated in Figure 2-14. Liquid hydrogen is transferred to the vehicle by either a pump or the pressure-transfer process. Liquid hydrogen is usually stored in vehicle tanks at pressures less than 50 psig, and so substantial pressures are not necessary during liquid hydrogen refueling. Pressure transfer requires the station tank pressure to exceed the vehicle tank pressure, and this can be accomplished if the station tank pressure has increased significantly (due to inherent heat leaks) since the last hydrogen delivery or if

it is increased with pressure-build circuit (which vaporizes some liquid in a heat exchanger and returns it to the tank ullage to create a "false head").

Liquid hydrogen dispensing stations include various control systems and plumbing components that enable the previously described functions associated with the refueling process. These include vapor-return circuits used during cool-down, purge gas circuits, pneumatic valve actuation equipment, flow meters and various transducers, computer controls, and code-compliant equipment enclosures. The specific design of these components and systems is usually proprietary to the system manufacturer.

3. STATION PERMITTING, CONTRACTING, AND INSTALLATION

Hydrogen fueling stations are currently permitted, contracted, and installed in California, primarily through individual site-specific efforts at the local level. Some stakeholders are finding the installation process challenging from the lack of state regulations that specifically apply to hydrogen fueling stations, resulting in local jurisdictions having to make permitting decisions with guidance from related regulations, codes of practice, and standards for equipment. Other stakeholders indicate that local jurisdictions are accustomed to making decisions based on a variety of codes and standards, and although more specificity to hydrogen fueling stations would be helpful, the lack of specific California State regulations is not a major barrier to fueling station installations.

Section 3.1 reviews these issues regarding the ways in which hydrogen fueling stations can be permitted. It explains the codes of practice and equipment standards that are relevant, various efforts to write more specific guidance documents, and the California State regulations for safety that apply to the installation design and equipment use. Section 3.2 discusses hydrogen fueling station siting, contracting, installation, startup, training, and maintenance issues.

3.1 Use of Codes, Standards, and Regulations in Permitting Facilities

A site owner or contractor who wants to install a hydrogen fueling station must make a case to the local permitting authorities that the planned station meets their safety requirements. One way to achieve this is by developing a building and equipment design that complies with well-known codes of practice, equipment standards, and government regulations. Although codes and standards are not necessarily regulatory requirements enforced by a state or federal agency, compliance with them is widely accepted as evidence of a safe design. Government agencies often adopt these codes and standards in their own laws and regulations, meaning that codes and standards frequently overlap state regulations. In California, the design must comply with state regulations for safety but the State is not involved in permitting the fueling station project.

Some of the most widely accepted standards and codes of practice are National Fire Protection Association (NFPA) standards and the National Electric Code. The International Code Council (ICC) also develops documents like the NFPA that describe safe practices and use of equipment built to particular standards, although ICC documents are not as well known in California; however, recent cooperation with the NFPA through efforts at the U.S. Department of Energy may bring many aspects of the ICC hydrogen codes into NFPA documents (Reference 44).

The equipment standard references in these documents have several sources, such as the American Society of Mechanical Engineers (ASME). Documents from the Society of Automotive Engineers (SAE) and the U.S. Department of Transportation (DOT) are also relevant, although these are generally more applicable to fuel delivery and on-vehicle hydrogen systems rather than the permanently installed fueling stations. Section 3.1.1 discusses these and other sources of codes and standards in further detail.

In conjunction with the local authority's approval of a design based on compliance with well-respected codes and standards, the design must meet the industrial safety sections of the State occupational safety and health regulations (Title 8, Chapter 4, of the California Code of Regulations). These regulations are established by a California State agency called Cal/OSHA. Although Cal/OSHA does not have the jurisdiction to permit a station, the station does need to comply with the regulations. For example, one subject area of those regulations that is pertinent to hydrogen fueling stations is the pressure vessel code.

So far, neither the Cal/OSHA regulations nor most of the common codes and standards frequently cited in California specifically address hydrogen fueling stations. As a result, installation of existing stations has depended on references to related codes and standards and Title 8 regulations. Section 3.1.1 reviews these related codes and standards.

3.1.1 Codes, Standards, and Regulations Process

As previously discussed, when attempting to site and permit a hydrogen fueling station with a local authority, it is necessary to reference applicable codes and standards, whether they are specific to hydrogen fueling stations or only related to the application. This section reviews the codes, standards, regulations, and recommended practices that are potentially applicable to hydrogen fueling stations. California regulations are given particular emphasis, because this guide is intended for California installations and because other codes and standards are reviewed in available documents (e.g., Reference 45).

Codes and standards are currently developed by a variety of organizations but they are not laws or regulations that, if followed, lead directly to a permit for facilities such as hydrogen fueling stations. Rather, experts in pertinent fields gather in working groups to develop codes or standards that can be adopted by enforcement agencies and permitting authorities.

It is important to understand the difference between codes, standards, and regulations. Codes are those documents that compile provisions across a broad subject matter. An example of a code is the National Electrical Code (NEC), which references NFPA standards in many areas to develop one comprehensive document on issues related to electric products and installation. Codes like the NEC often recommend particular practices for various circumstances that will ensure a safe environment. Standards, unlike codes, cover specific applications or products, such as NFPA 50A for gaseous

hydrogen systems and 50B for liquid hydrogen systems. SAE recommended practices are much like NFPA standards, but they apply mainly to the on-vehicle aspects (of hydrogen refueling, in this case). The term standard can also refer to a document that indicates that a piece of equipment, such as a particular type of pressure vessel, is produced to meet safety specifications. Codes and standards are often adopted by governmental enforcement agencies, in which case they become enforceable regulations. Table 3-1 lists organizations that are involved in the development of codes, standards, recommended practices, and regulations for hydrogen vehicles and fueling facilities.

Table 3-1. Organizations involved in the development of codes, standards, recommended practices and regulations related to hydrogen fueling.

Organization	Role
International Code Council, Inc. (ICC)	Code and standard development
Building Officials and Code Administrators International (BOCA)	Code and standard development
International Conference of Building Officials (ICBO)	Code and standard development
Southern Building Code Congress International, Inc. (SBCC)	Code and standard development
National Fire Protection Association (NFPA)	Code and standard development
International Organization for Standards (ISO)	Code and standard development
Society of Automotive Engineers (SAE)	Recommended practices
Underwriters Laboratories (UL)	Standards for equipment
Institute of Electrical and Electronics Engineers (IEEE)	Standards for equipment
American Society of Mechanical Engineers (ASME)	Standards for equipment
International Electrotechnical Commission (IEC)	Standards for equipment
Compressed Gas Association (CGA)	Standards for equipment
U.S. Department of Transportation (DOT)	Regulations for transportation of fuels and Federal Motor Vehicle Safety Standards
U.S. Occupational Safety and Health Administration (OSHA)	Regulations for on-site safety of employees
California Occupational Safety and Health Administration (Cal/OSHA)	Regulations for on-site safety of employees in California
California Highway Patrol (CHP)	Regulations for automotive equipment safety in California
U.S. Department of Energy (DOE), National Renewable Energy Laboratory (NREL), in cooperation with National Hydrogen Association (NHA)	Coordinating efforts of various organizations to develop hydrogen codes and standards

Some of these organizations have experience with compressed and liquefied natural gas vehicles and fueling stations. Their involvement in the development of hydrogen codes is helpful because their experience with refueling natural gas vehicles provides a relevant background for hydrogen refueling infrastructure and on-vehicle systems. Natural gas and hydrogen, stored as either compressed gases or cryogenic liquids,

have certain similar characteristics. Therefore, some stakeholders believe that established codes and standards for industrial hydrogen applications provide a more appropriate point-of-departure for developing compressed and liquid hydrogen automotive fuel codes. Other stakeholders believe that established codes and standards for industrial hydrogen applications provide a more appropriate point-of-departure, because natural gas and hydrogen properties differ in various important respects (Reference 46). In fact, industrial-installation hydrogen codes have been the primary references cited in permitting the hydrogen fueling stations that have been installed to date in California (see Appendix A).

General and specific codes and standards potentially affecting hydrogen fueling stations are discussed in the following sections. Section 3.1.1.1 summarizes these codes and standards; Section 3.1.1.2 addresses California regulation development; and Section 3.1.1.3 focuses on California regulations affecting compressed hydrogen storage tanks.

3.1.1.1 Current Codes and Standards and Those in Development

Currently, hydrogen refueling equipment and station designs, and site/installation plans can reference several codes and standards that relate to hydrogen or gaseous refueling applications.

Several groups in the United States and other countries are working to modify existing codes and draft new codes and standards to address hydrogen use as an automotive fuel (and also for stationary fuel cell applications). Many of these groups are cooperating in this effort. For example, under the U.S. Department of Energy (DOE) sponsorship, the National Renewable Energy Laboratory (NREL) and National Hydrogen Association (NHA) have organized the DOE Hydrogen Codes and Standards Coordinating Committee (HCSCC).

The mission of the HCSCC is to coordinate the development and implementation of a consistent set of hydrogen-related codes and standards that will ensure the safe production, delivery, and use of hydrogen, and facilitate the accelerated commercialization of hydrogen technologies for stationary, transportation, and portable applications. In addition to serving as the data base repository, clearinghouse, and gatekeeper for the codes and standards activities being conducted within DOE, the HCSCC will also reach out to and collaborate with other national and international organizations involved in codes and standards activities to promote the sharing and dissemination of this information (Reference 47).

Many of the previously discussed organizations such as the NFPA, ICC, SAE, ASME, and others are supporting the HCSCC work. The HCSCC has periodic meetings to facilitate and coordinate the progress of hydrogen codes and standards development efforts. The agendas and minutes of these meetings are generally posted on the NHA Website (Reference 48). Separate from but in support of the HCSCC work, many organizations such as ASME, SAE, and NFPA have organized committees to develop

hydrogen-related codes, standards, and recommended practices. Examples of this work will be discussed subsequently.

NREL is also working to produce hydrogen safety and permitting guidance documents, which relate to the HCSCC. For example, in cooperation with the NFPA, NREL has published a "Handbook of Representative Hydrogen Fueling Station Projects for Fueling Fuel Cell-Powered Vehicles" in draft form (Reference 15). NREL, Pacific Northwest National Laboratory, NFPA, and ICC are also cooperating to produce a document titled "How to Permit a Hydrogen Fueling Station Guidebook for Permitting Officials" (Reference 45).

Table 3-2 lists some of the current codes and standards and those in development. More detailed lists are available from the NHA (Reference 48) or NREL (Reference 47). Some provisions of these codes and standards have been adopted into law in California, e.g., by Cal/OSHA and the California Highway Patrol, making them part of the California Code of Regulations (CCR). Most of the current codes and standards listed in Table 3-2 do not refer specifically to hydrogen fueling stations.

Of particular note is the progress of hydrogen inclusion into NFPA 52. The NFPA hydrogen working group is expanding NFPA 52 to cover compressed hydrogen and possibly liquid hydrogen. Footprint and ventilation is likely to mirror guidance for hydrogen in the 2003 ICC Fuel Gas Code (Reference 44).

The hydrogen section of Chapter 7 of the ICC Fuel Gas Code has recently been released and contains specifications for many aspects of hydrogen refueling. In addition, the ASME Hydrogen Steering Committee is in the process of addressing a potential new Section VIII, Division 3 code case for composite storage tanks in stationary applications, such as fueling stations (Reference 49). This new code case may be fast-tracked with the standards committee.

Organizations in the U.S. and other countries are developing other reference documents, such as those listed in Table 3-3. Although these organizations are developing potentially useful documents for hydrogen vehicles and infrastructure, California State agencies like Cal/OSHA and the CHP have not traditionally adopted these types of references when forming regulations. Instead, they have historically depended mainly on ASME, NFPA, and SAE references; however, local authorities could possibly accept citations from these documents in the permitting process, and codes being developed by U.S. organizations may be harmonized with codes developed by non-U.S. organizations.

Many stakeholders are hoping that the development of codes and standards for the hydrogen automotive applications in California will proceed at a much faster pace than has occurred with compressed and liquefied natural gas. Although it is evident that codes, standards, and regulations specific to hydrogen fueling stations are not essential for permitting limited use demonstration stations (as shown by the successful installation of existing hydrogen refueling stations in California), they will make the permitting and installation process simpler, more uniform, and less time-consuming.

This point was discussed at length during a meeting of various California stakeholders in March 2003 at the South Coast Air Quality Management District (SCAQMD). The meeting was organized by USA PRO & Associates and was attended by representatives from hydrogen product vendors, gaseous fuel experts, the California

Table 3-2. Example of codes, standards, and regulations potentially applicable to hydrogen fueling stations

Organization	Code, Standard, or Regulation	Status/Reference
NFPA	50A — Gaseous Hydrogen Systems at Consumer Sites	NFPA is working to develop standards for hydrogen stations. NFPA 50A and 50B will be combined in NFPA 55.
NFPA	50B — Liquid Hydrogen Systems at Consumer Site	
NFPA	52 — CNG Vehicular fuel Systems	These NFPA CNG and LNG vehicle standards are related to hydrogen vehicles. NFPA is working to include hydrogen in these standards, which may be combined
NFPA	57 — LNG Vehicular Fuel Systems	
NFPA	30A — Motor Fuel Dispensing Facilities and Repair Garages	Current
NFPA	1 — Uniform Fire Code	Current
ASME	Boiler and Pressure Vessel Code, Section VIII	These are current codes. ASME has formed a Hydrogen Steering Committee to address hydrogen vehicle codes.
ASME	B31.3 — Process Piping	
CGA	G 5.4 — Standard for Hydrogen Piping at Consumer Locations	Current
CGA	G 5.5 — Hydrogen Vent Systems	Current
ICC	International Fuel Gas Code	HCSCC is working with ICC to address hydrogen vehicle requirements.
ICC	International Building Code	
SAE	J2600 — Recommended Practice for Hydrogen Refueling Connection Devices	Published
SAE	J2578 — General FCEV Safety	Published
SAE	J2579 — Hydrogen Vehicle Fuel Safety Systems	Being drafted (not yet balloted)
SAE	J2601 — Refueling Communication Device/Protocol	Being drafted (not yet balloted)
ANSI/AGA	NGV 1 — CNG Vehicle Fueling Connection devices	These current NGV standards are related to hydrogen vehicle applications
ANSI/AGA	NGV 2 — Basic Requirements for CNG Vehicle Fuel Containers	
ANSI/AGA	NGV 4.1 — NGV Dispensing Systems	
ANSI/AGA	NGV 4.4 — Breakaway Devices for Natural Gas Dispensing Hoses	
U.S. DOT	CFR Title 49, Parts 100-199, Transportation of Hazardous materials	Applies to hydrogen transportation
U.S. DOT	CFR Title 49, Part 571, Federal Motor Vehicle Safety Standards (FMVSS)	May need revision to include hydrogen
CHP	CCR, Title 13 (Motor Vehicles), Division 2 (CHP), Chapter 4 (special equipment)	Currently addresses CNG and LNG, being modified to include hydrogen
California OSHA	CCR, Title 8 (DOSH), various sections including Unfired Pressure Vessel Safety Orders	Many parts of current Title 8 apply to hydrogen fueling stations.

Acronyms:
NFPA — National Fire Protection Association
ASME — American Society of Mechanical Engineers
CGA — Compressed Gas Association
ICC — International Codes Council
SAE — Society of Automotive Engineers
ANSI — American National Standards Institute
AGA — American Gas Association

DOT — Department of Transportation
CFR — Code of Federal Regulations
CHP — California Highway Patrol
CCR — California Code of Regulations
OSHA — Occupational Safety and Health Agency
DOSH — Department of Occupational Safety and Health

Table 3-3. Examples of additional references being developed that are potentially applicable to hydrogen fueling stations.

References	Organization (Country)
Liquid H_2 – Land Vehicle Fueling System Interface	SCC (Canada)
Airport H_2 Fueling Facility	DIN (Germany)
Gaseous H_2 and H_2 Blends – Vehicular Fuel Systems	ANSI (USA)
Basic Requirements for Safety of H_2 systems	DIN (Germany)
Liquid H_2 – Land Vehicle Fuel Tank	SCC (Canada)
Tank Containers for Modal Transport of Liquid H_2	SCC (Canada)

Acronyms:
SCC — Standards Council of Canada
DIN — Deutshes Institut fur Normung
ANSI — American National Standards Institute

Fuel Cell Partnership, NREL, Cal/OSHA, and the California Highway Patrol. Several participants stated that although they do not want a lengthy new set of regulations and permitting requirements from the State, new industry-accepted codes and standards will speed up the process of permitting by local authorities. During the period of demonstration projects, which is likely to last several years, a more streamlined approach to design and installation will enable a hydrogen infrastructure to be initiated before the commercial market for automotive use of hydrogen is fully developed. In addition, uniformity in design and approach will be especially important as the applications for hydrogen refueling expand to include retail, public access facilities.

3.1.1.2 California Regulation Development

As mentioned in the previous section, Cal/OSHA develops state regulations for workplace safety. In addition, the California Highway Patrol (CHP) develops regulations related to transportation. The two agencies adopt appropriate codes and standards into regulations pertaining to their respective areas of responsibility and jurisdiction. In general, the CHP handles issues related to registered highway (on-road) vehicles, including heavy-duty vehicles that transport fuel, while Cal/OSHA handles health and

safety issues at a particular site. For refueling stations, Cal/OSHA's regulations are most relevant to the delivery, storage, and dispensing of hydrogen from pressure vessels, but may also include storage on vehicles that are located on a property, whether registered or not. Table 3-4 summarizes the involvement of each agency in applications potentially related to hydrogen fueling stations.

In forming regulations, Cal/OSHA seeks input from automotive and engineering experts with gaseous alternative fuels and high-pressure vessel experience. The CHP also

Table 3-4. California Agencies involved in Development of Hydrogen Vehicles and Fueling Stations

Type of Application	Agency
Highway Vehicles	California Highway Patrol – CHP, CCR Title 13 Section 930-937
On-Road Transportation of Hydrogen	California Highway Patrol – CHP, CCR Title 13 Section 1150-1194
Fueling Stations	Dept. of Safety and Health – Cal/OSHA, CCR Title 08 Pressure Vessel Code, Chapter 4, Subchapter 1
Mobile Fueling	Dept. of Safety and Health - Cal/OSHA, CCR Title 08 Pressure Vessel Code, Chapter 4, Subchapter 1
Unlicensed Vehicles	Dept. of Safety and Health - Cal/OSHA, CCR Title 08 Pressure Vessel Code, Chapter 4, Subchapter 1

seeks input from industry (e.g., automotive manufacturers). As NFPA, SAE, ASME, and other codes and standards organizations develop further guidelines pertaining to various aspects of hydrogen fueling and vehicles, both agencies will look to these documents for guidance in developing their safety regulations.

Although Cal/OSHA adopts regulations governing the safety at refueling sites, it is important to note that it does not have the authority to permit the facilities. As a result, it is not necessary to submit facility designs to Cal/OSHA; however, if it is difficult to obtain local permits for installing a refueling station, a representative from Cal/OSHA can be retained to inspect the plans for compliance with regulations and submit a support letter to the local authority with jurisdiction.

3.1.1.3 Cal/OSHA Regulations for Storage Tanks

Recently, there has been uncertainty in California about the use of particular types of hydrogen storage tanks at refueling facilities. Although there are approved DOT pressure vessels for flammable gas storage, Title 8 Section 460(b) requires that permanent storage tanks must be ASME stamped. According to Don Cook, Principal Safety Engineer at Cal/OSHA, DOT-stamped tanks may be used in transporting hydrogen to the facility or in fueling vehicle tanks directly, but may not be installed on site (Reference 49). For example, if natural gas is being reformed on-site with the

hydrogen compressed and then stored in a pressure vessel, the vessel must be ASME-stamped.

At this time, carbon fiber or fiberglass reinforced tanks, also known as composite tanks, may not be used for permanent storage on-site even though they are permitted for gaseous storage in on-vehicle tanks. On-vehicle composite tanks have not been certified with the same margin of safety for working pressure as ASME tanks used for stationary storage.

Cal/OSHA reports that ASME is currently developing guidance on composite material pressure vessels. The agency expects to make revisions to regulations as soon as ASME develops new code cases for stationary use of these tanks. In addition, the Cal/OSHA Pressure Vessel Unit is currently investigating the use of composite storage tanks at a hydrogen refueling station for a possible site-specific variance. The outcome of that decision will provide more guidance on the type of storage tanks that are permitted for hydrogen refueling facilities.

3.1.2 Aspects of Current Codes that may be Important in Hydrogen Fueling Stations

As discussed in Section 3.1.1.1, many types of documents can be referenced for hydrogen transport, storage, refueling, and use in vehicles (see Table 3-2). For gaseous and liquid hydrogen use in and around buildings, the codes and standards specify various requirements including placement and type of equipment, ventilation, and obligations for sensors and alarms, as shown in Table 3-5. These potential requirements for hydrogen fueling stations are referenced mainly in documents like the National Electrical Code, NFPA 50A (gaseous hydrogen), NFPA 50B (liquid hydrogen), NFPA 52 (CNG refueling stations), and NFPA 57 (LNG refueling stations). In addition, the Chapter 7 of the ICC Fuel Gas Code provides guidance on many aspects of hydrogen fueling systems. It specifically addresses hydrogen vehicle fueling, unlike the NFPA documents to date. Table 3-6 indicates the topics that this code addresses. Local authorities review permit applications to learn if the applicant has addressed issues such as those listed in Tables 3-5 and 3-6 and has cited the appropriate codes. For example, typical phraseology for an automotive gaseous refueling station permit application is as follows, "The system shall be designed in full compliance with the latest edition of applicable sections of the following codes, standards, and guidelines. Where conflict exists, contractor shall follow the most stringent requirements." The applicable references are cited in the documentation.

Table 3-5. Issues addressed in current codes and standards that impact hydrogen fueling station design.

Location/Type of Equipment	Electrical/Heating Classification	Ventilation	Sensors and Alarms
• Location of vehicles and fueling equipment and proximity to sensitive areas [a] • Total volume of fuel stored • Proximity of stored volume to sensitive areas • Existence of valves, flanges, and other connectors that could leak	• Classification of locations • Potential leak sources • Ceiling area • Open flame heaters • Electrical equipment • Lighting	• Requirements for mainly outdoor facilities • Requirements for portions of facilities that are indoors • Options for mechanical continuous, non-mechanical continuous, or sensor activated solutions	• Necessity for flame detection • Necessity for gas detection • Types of alarms

[a] Potential ignition sources, entryways, roads, sidewalks, property lines.

Table 3-6. Relevant topics to vehicle fueling addressed in the ICC Fuel Gas Code for hydrogen systems.

Section	Topic
703 – General Requirements	• Footprint size • Maximum hydrogen output volume • Number of vehicles permitted in a space • Ventilation • Configuration and types of pressure vessels and pressure devices • Electrical design
704 – Piping, Use and Handling	• Location of piping systems • Design and installation of piping systems • Avoidance of physical damage • Controls
706 – Location of Gaseous Hydrogen Systems	• Requirement for hydrogen cutoff rooms and exceptions • Gas detection, alarms • Control of ignition sources • Explosion control

3.1.3 The Permitting Process

Site construction activities are normally subject to permit processes by city and/or county agencies such as planning, building, and fire departments. For unique or lesser-known automotive fuels, such as hydrogen, more comprehensive plan checks or other procedures can be required by the individual city or other governing agencies. In the case of hydrogen, the site owner should be especially diligent in researching and investigating all parties who will determine the project's permitting requirements. The

organization, office, or individual responsible for approving the station is referred to as the Authority Having Jurisdiction (AHJ).[8] The basic steps commonly involved in the permitting process are listed in Table 3-7, although these steps can differ depending on local procedures and the AHJ. The steps listed in Table 3-7 are based on experience and discussions including References 45, 50, and 51. The novel nature of hydrogen for automotive applications requires special diligence by the site owner and a thorough understanding of the product, application, and workings of the agencies. In all cases, during the permitting process, the parties involved should retain copies of all questions raised and the follow-up letters of confirmation. This diligence will provide a record that the project was in compliance with the local authorities at the time of construction.

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[8] As explained in most NFPA documents, there may be multiple AJHs because the jurisdictions and responsibilities are different for different agencies, and because multiple departments may be involved in approvals and permitting. Example AHJs include the local fire marshal or chief of the fire, building, or planning department.

Table 3-7. A typical initial checklist for beginning the permitting process for a hydrogen fueling station (References 45, 50, and 51)

Checklist
• Determine the role of local jurisdictions such as fire, planning, and building departments
• Contact appropriate agencies and/or the Authority Having Jurisdiction (AHJ)
• Initially describe the project and seek "gut level" concerns
• Identify and contact experts who can help address these concerns
• Refer AHJ to other AHJs who have approved similar projects in their jurisdictions
• Assess the need for community outreach or education programs
• Apply for needed building, fire, and other permits
• Pay all applicable construction, license, and other fees
• Maintain close contact with the AHJ while developing documents and during the review process

The site owner should also be aware of the role of certain agencies that do not literally issue hydrogen fueling station permits. An example is Cal/OSHA, as it does not require a permit or inspection at this time. Cal/OSHA is available, however, to inspect the design and provide a letter of compliance. Should an accident occur, the site owner will be required to provide all of the necessary documentation, and in some cases, engineering justification to Cal/OSHA and the Federal OSHA. As a result, a letter of compliance from Cal/OSHA could be helpful, especially until more hydrogen fueling station specific codes, standards, and regulations are widely adopted.

Another example of a unique set of circumstances is the City of Los Angeles, which has its own independent Pressure Vessel Group. Some government properties may not require permitting, and this may or may not be true of a transit agency, for example. It is important to ask other parties who have been involved in hydrogen infrastructure or natural gas fueling station projects about their experiences in the city or county since every locality has its own regulations and procedures.

Most importantly, the site owner must perform due diligence. This may involve, for example, enlisting the support of a California registered engineer with expertise in this field to review station design and installation plans. In addition, the development of a HAZOP or process safety analysis by a California registered engineer with expertise in siting, fire protection/detection, and gas detection is a high-priority item.

3.2 Station Siting, Contracting, Installation, Startup, Training, and Maintenance Issues

3.2.1 Station Site Requirements

The codes, standards, and regulations discussed in Section 3.1 essentially dictate the station site requirements. These requirements include distances from other land uses, area classifications, footprint size, and restrictions on the volume of gas produced on-site.

Minimum distances for storage of compressed gases from various objects are addressed in NFPA 50A and 52, which apply to compressed hydrogen gas at consumer sites and CNG at fueling stations, respectively. Table 3-8 lists these restrictions on distances. Research is currently underway to determine the specific separation distances most appropriate to hydrogen fueling stations (Reference 52).

Table 3-8. Minimum required distances of compressed hydrogen and CNG storage vessels from various buildings, property lines, or combustible materials.

Sensitive Area	H_2	Code Reference	CNG	Code Reference
Public sidewalks and parked vehicles	15 feet	*NFPA50A: 3-2*	10 feet	*NFPA52: 4-4*
Place of public assembly	25-50 feet	*NFPA50A: 3-2*	—	—
Line of adjoining property that may be built on	5 feet	*NFPA50A: 3-2*	10 feet	*NFPA52: 4-4*
Building with non-combustible walls adjacent	0-25 feet	*NFPA50A: 3-2*	10 feet	*NFPA52: 4-4*
Building with other material wall	10-50 feet	*NFPA50A: 3-2*	10 feet	*NFPA52: 4-4*
Flammable liquids above ground	10-50 feet	*NFPA50A: 3-2*	20 feet	*NFPA52: 4-4*
Flammable gas storage, either high or low pressure	10-50 feet	*NFPA50A: 3-2*	3-5 feet	*CCR Title 8-531[a]*

[a] California Code of Regulations Title 8, Subchapter 1, Article 7, Section 531 is generally in accordance with NFPA 52.

The practicality of sizing the fueling station for reasonable operations is an important siting issue. New ICC hydrogen guidance in Chapter 7 of the Fuel Gas Code restricts the volume of gas produced and the footprint of the fueling space. In addition, Chapter 22 of the International Fire Code dictates where on the property a hydrogen facility may be located. These codes should be reviewed when considering the fueling station site.

Hydrogen fueling station siting should also take growth potential into account. Sections 2.2.3 and 2.2.4 discussed the effects of growth considerations on station capacity calculations and equipment (e.g., compressor) selections. When developing the station

site plan, potential growth should also be considered for factors such as accommodating additional vehicle traffic, possible additional equipment (e.g., compressed or liquid storage vessels, dispensers), and code-required separation distances.

3.2.2 Site Selection Guidance

In the near term, hydrogen fueling stations will likely continue support of demonstration fleets, e.g., relatively small numbers of hydrogen-fueled prototype light-duty vehicles or transit buses. These fleets mainly rely on dedicated fueling stations at this time. A network of fueling facilities placed in strategic locations may also begin to supply hydrogen along selected "hydrogen highways." Near-term site selection is therefore based upon specific fleet or project requirements, and the resulting site selection issues are quite different from those for public-access retail gasoline stations. While hydrogen strategy planners envision integrating hydrogen fueling into existing retail gasoline stations, no such stations exist in California at this time (e.g., see the station profiles in the appendix), and guidelines for these types of stations are not presented here.
Due to the relationship of fueling stations to fleets, site selection is based upon the location of the fleet terminal and transportation pattern of the fleet, the fuel demands, and codes that may restrict the delivery of hydrogen, the installation of hydrogen-production equipment, or the presence of hydrogen vehicles. Sites that produce hydrogen on-site may have fewer siting challenges than stations that plan to store large amounts of hydrogen. Also, the choice between storage of liquid hydrogen or gaseous hydrogen may also have siting consequences. As with all aspects of building a hydrogen fueling station, the applicable standards for gaseous and liquid hydrogen should be referenced. The use of a FMEA or HAZOP process can also help determine whether a site is appropriate. These analyses study all possible types of failures and effects and reflect the site and station characteristics.

3.2.3 Contracting for Station Design and Installation

Contracting for hydrogen fueling station design and installation is often constrained by the fleet or site owner's contracting procedures and/or restrictions associated with the source of the funds. Because hydrogen fueling stations are relatively unusual and permitting is not routine, these procedures and restrictions can be a challenge for efficient station installation contracting.
For example, transit agencies (which may need hydrogen fueling facilities for fuel cell buses) are most commonly a form of local government or joint powers authority. As such, they usually follow public works contracting procedures, which require a two-phase process for facilities such as fueling stations: a request for qualifications (RFQ) for the design, followed by an invitation for bid (IFB) for the construction[9]. Parties

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[9] The firm or consultant hired for the first (design) phase sometimes serves as a project manager for the second (construction) phase.

involved in the first phase are usually precluded from being equipment suppliers in the second phase. This can present a dilemma in the case of a hydrogen fueling station because firms with appropriate design capabilities (e.g., electrolyzer manufacturers, reformer manufacturers, industrial gas companies) may also wish to supply equipment and/or be involved in the construction. If these firms are not involved in the design phase, a less-than-optimum design can result, and this can produce problems ranging from costly redesign during the construction phase to disagreements regarding which firm is responsible for any subsequent station performance problems. Rigid application of separate design-build contracting can also present problems when designs are regarded as proprietary by participating firms.

These contracting procedures and restrictions have resulted in delays, increased costs, and alleged performance problems for prior CNG, LNG, and hydrogen fueling station installations. Experience indicates that success is enhanced when the public agency engineering staff and contracting department are able to cooperate and interpret contracting procedures to fit the unusual requirements of a hydrogen fueling facility. For example, the scope of the design phase can be defined to include the general architectural aspects of the project and the general performance specifications of the hydrogen fueling requirements. The installation contract can then include the technical design and equipment details of the hydrogen fueling system, in which case the installation contractor (which is usually a team consisting of a construction general contractor and the hydrogen equipment designer/supplier) is clearly responsible for the successful operation of this system.

Of course, private fleets or sites that install hydrogen fueling stations without government funding assistance are not constrained by public works contracting procedures. In this case, a combined design-build contract may be the best way to procure the hydrogen fueling station. Assuming that the station is procured through a competitive proposal process, the solicitation should contain at least a detailed specification package (including performance requirements, fleet characteristics, and site conditions), proposal content instructions, and evaluation criteria.

3.2.4 Station, Startup, Training, and Maintenance

The startup phase, also referred to as the commissioning phase, usually includes initial operation, troubleshooting, debugging, tuning, testing, and commissioning of the hydrogen fueling station. The startup phase usually concludes with acceptance testing wherein the site owner cooperates with the installation contractor to demonstrate that the station meets all the performance criteria specified in the contract. These criteria depend on the type of station, but they generally include performance specifications (e.g., dispensing rate, metering accuracy, hydrogen generation rate and/or storage capacity), safety system checks (e.g., emergency shutdown, response to various faults, system restart), and sometimes durability and reliability tests.

Prior to acceptance, the contractor provides the site owner with design, operation, and safety documentation, which includes items such as: as-built stamped drawings, specifications and instructions for all station components, operating manuals, certification forms for all ASME pressure vessels, radiographic test films for pipe welds, etc.

The installation contractor almost always provides initial station operation and maintenance training; however, there are options for additional training, and the extent of these additional training requirements depends on the type of site and vehicle fleet operation. For example, transit properties usually require training of service workers (not drivers) for fueling and facilities personnel for station maintenance. In many trucking fleets, trucks are refueling by drivers who must be trained. When non-fleet public ownership of light-duty hydrogen vehicles evolves, it is assumed that refueling instructions will be contained in the vehicle-operating manual, and the retail station owner will attend to station maintenance.

Key components of the training program should include safety, refueling, troubleshooting, and maintenance. Some fleets (particularly transit agencies) have internal training departments that develop training programs by combining the training instructions and material provided by the station installer with procedures that have proven to be effective for that fleet's employees. These training programs, which would include hydrogen fueling station operation and maintenance, are periodically conducted for new hires and as refresher courses. Alternatively, the fleet can contract with outside firms to provide training programs. A number of specialized firms have evolved that develop proven training programs and resources that cover CNG, LNG, and hydrogen fueling station operations. Programs are available that focus exclusively on safety, and other training programs cover the whole spectrum of station operation and maintenance. Some of the firms that provide these training programs are also station designers, equipment manufacturers, or fuel providers. Many firms have found it to be more efficient to contract for training than to develop internal training programs.

Hydrogen fueling station maintenance requirements are inter-related with the station and equipment warranty provisions, and the spare parts inventory that is usually specified in the contract. Station maintenance may be performed by in-house staff or by contract with an outside firm. Outside firms can provide any combination of scheduled and unscheduled maintenance, and firms that provide these maintenance services are often also station designers, equipment manufacturers, or fuel providers. In some cases, options regarding in-house versus contracted maintenance are affected by union agreements.

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APPENDIX A. PROFILES OF HYDROGEN FUELING STATIONS IN CALIFORNIA

- California Fuel Cell Partnership, West Sacramento Station

- SunLine Transit Agency, Thousand Palms Station

- American Honda Motor Company, Torrance Station

- California Fuel Cell Partnership, Richmond Station

- BMW of North America, Oxnard Station

CALIFORNIA FUEL CELL PARTNERSHIP

WEST SACRAMENTO HYDROGEN FUELING STATION

The California Fuel Cell Partnership Station has dispensers to fuel vehicles with 3,600-psi hydrogen, 5,000-psi hydrogen, or liquid hydrogen.

The California Fuel Cell Partnership (CaFCP) is a collaboration of automobile companies, fuel providers, fuel cell technology organizations, and government agencies seeking to commercialize fuel cell vehicles. Information regarding the CaFCP members, organizational structure, goals, and accomplishments is available at the Partnership's website: www.fuelcellpartnership.org. The CaFCP occupies a 4.5-acre headquarters facility in West Sacramento, which includes administration offices, an exhibit area, garage bays for ten fuel cell vehicle partners, a methanol fueling station, and a hydrogen fueling station. This profile focuses on the hydrogen fueling station.

The CaFCP West Sacramento station dispenses compressed hydrogen at 5,000 psi or 3,600 psi, and it also dispenses liquid hydrogen.[*] The station stores liquid hydrogen in a 4,500-gallon gross capacity vacuum-jacketed cryogenic tank. The hydrogen is usually maintained near a 30-psig and -415°F saturation state by a pressure-regulation and

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[*] The liquid hydrogen dispensing capability was added to the CaFCP station after it was initially installed in mid-2000. As of the end of 2002, the liquid hydrogen dispenser has been installed and tested, but final operation approvals have not yet been obtained.

vent system. At this condition, the maximum liquid capacity of the storage tank is approximately 1,100 kg. Hydrogen used for compressed hydrogen fueling is boiled and warmed in an ambient-air vaporizer. The gas is then compressed by a five-stage reciprocating compressor into three high-pressure storage vessels. These tube-shaped vessels have a capacity of approximately 43 kg at 6,250 psi. This vaporize-and-then-compress strategy is well suited to this station's usage profile, even though it is less energy efficient than a pump-and-then-vaporize strategy. During periods of infrequent station use and low hydrogen throughput, all or some of the boil-off hydrogen can be compressed into the high-pressure vessels and this minimizes the need to vent hydrogen to the atmosphere.
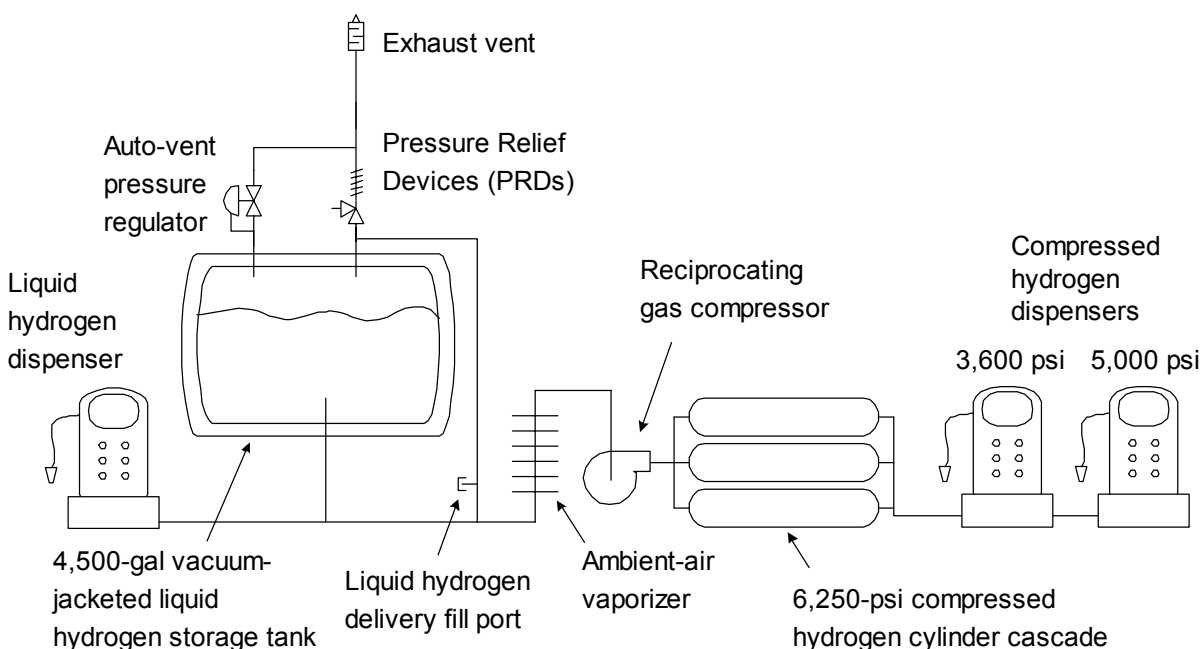
Simplified schematic illustration of the CaFCP hydrogen fueling station design

The accompanying simplified schematic diagram illustrates the basic design of the CaFCP hydrogen fueling station. The station's key features and specifications are summarized in the accompanying table. The photographs show different views of the station and its components, which are explained in the captions.

The CaFCP station was jointly designed and installed by six of the partnership's energy and gas company members: BP, ExxonMobil, Shell Hydrogen, ChevronTexaco, Air Products and Chemicals (APCI), and Praxair. APCI provided the compressor, compressed hydrogen storage vessels, dispensers, and overall project management. Praxair supplied the liquid hydrogen storage tank and vaporizer. The station itself is co-owned by BP, ExxonMobil, Shell Hydrogen, ChevronTexaco, APCI, and Praxair. Liquid is delivered to the station in cryogenic tank trucks by APCI (from a hydrogen liquefaction

plant near Sacramento) and Praxair (from a hydrogen liquefaction plant near Los Angeles).

Refueling compressed-hydrogen vehicles at the CaFCP station is automated, and the station can accommodate vehicles that are or are not equipped to transmit fuel tank data through a cable that is connected to the vehicle before the nozzle is attached. For vehicles that can transmit the fuel tank pressure and temperature, the station has the capability to adjust the fill pressure and/or advise the refueler to let the vehicle tank

Hydrogen delivery and storage	Liquid hydrogen, delivered by cryogenic tank truck
Hydrogen dispensing capability	Two compressed hydrogen dispensers: 5,000 psi at nominal 0.25 kg/min (slow fill) to 2 kg/min (fast fill), 3,600 psi at nominal 1 kg/min (slow fill) to 2 kg/min (fast fill). One liquid hydrogen dispenser, rate depends on vehicle conditions.
Liquid hydrogen storage tank	Praxair (Taylor-Wharton) 4,500-gallon gross capacity vacuum-jacketed vessel, ASME-coded, 150-psi MAWP, 1 to 2 %/day normal evaporation rate
Vaporizer	Ambient-air vaporizer
Compressor	Greenfield 5-stage reciprocating compressor, intercooled, lubricated, 60-hp elect motor driven, 100 scfm
Compressed hydrogen storage	Three CPI carbon-steel tubes, each 17 ft^3 (water volume), ASME-coded, 7,255-psi design pressure, 6,250-psi maximum working pressure in this application, 43 kg total hydrogen storage capacity at this condition, priority-sequenced-cascade connection to dispensers
Compressed hydrogen dispensers	APCI dispenser, Sherex or WEH nozzles, 3,600-psi nozzle will fit 5,000-psi receptacle but not vise-versa, hose break-away connectors, heat-of-compression compensation for vehicles with fuel tank P&T instrumentation, capability to fill vehicle tanks with no communications
Liquid hydrogen dispenser	Pressure-transfer through vacuum-jacketed hose to Linde nozzle with vapor return, manual controls with automatic safety interlocks, and venting of returned vapor at this time
Example safety features and equipment	IR/UV fire detection, various pressure-relief devices and vents, station equipment enclosed in chain-link fence and protected by bollards, meets NFPA 50B siting criteria, meets ASME pressure vessel and piping codes, screening wall between station and Interstate 80, system received HAZOP review and FMEA, PIN-authorization system limits use to qualified and trained personnel
Area occupied by station	Approximately 2,000 ft^2 (not including setbacks)

Summary of CaFCP hydrogen fueling station key features and specifications

pressure settle in order to compensate for heat-of- compression effects that would otherwise preclude a full fill. For 3,600-psi hydrogen vehicles that cannot transmit fuel tank pressure and temperature data, the dispenser stops refueling when the appropriate pressure is reached, pauses for 10 seconds, and resumes refueling if the pressure has decreased. For 5,000-psi hydrogen vehicles that cannot transmit fuel tank pressure and temperature data, the dispenser fills at a fixed slow flow rate up to a shutoff pressure that includes an approximate heat-of-compression correction. Liquid hydrogen vehicle refueling is manually controlled at this time. The Linde nozzle delivers liquid hydrogen while simultaneously returning vapor (e.g., produced by refueling plumbing cool-down) back to the station.

The CaFCP station was designed to conform to industrial gaseous and liquid hydrogen customer-site system standards NFPA 50 A and B, respectively. The liquid and compressed hydrogen vessels were designed, fabricated, and tested consistent with the ASME Boiler and Pressure Vessel code. The design and installation of the station mechanical and electrical components conform to other applicable codes and standards such as the National Electric Code and Uniform Fire Code.

The station is equipped with various safety features (many of which are visible in the accompanying photographs) such as: pressure relief devices to vent hydrogen in case the liquid storage inner tank leaks or the pressure exceeds established limits, pressure relief devices to vent hydrogen if the high-pressure storage tank pressures exceed established limits, a chain-link fence enclosing all station components except the compressed hydrogen dispensers, bollards protecting the station from vehicle impacts, a 75-foot separation from adjacent buildings, a concrete wall between the station and Interstate 80, IR/UV fire-detection sensors that trigger alarms and safe shut-down sequences, nozzle designs that preclude refueling a 3,600-psi vehicle from a 5,000-spi dispenser, and a PIN-authorization system to restrict refueling operations to trained and qualified personnel.

The City of West Sacramento agencies involved in permitting the CaFCP station included the planning, building, fire, and HAZMAT departments. This process proceeded smoothly considering the unusual nature of hydrogen vehicle fueling stations. Care was taken to engage these agencies at an early stage and to provide them with all appropriate background information. In addition to features normally required by applicable codes and standards, the fire department requested the concrete wall to screen the station from Interstate 80 traffic.

Liquid hydrogen from the cryogenic storage tank is vaporized and warmed in an ambient-air vaporizer.

A 5-stage reciprocating compressor boosts the hydrogen gas pressure to 6,250 psi.

High-pressure hydrogen is stored in a three-vessel cascade.

Separate dispensers provide 5,000-psi and 3,600-psi compressed hydrogen fueling.

The liquid hydrogen dispensing hose and nozzle are holstered behind a locked gate.

SUNLINE TRANSIT AGENCY

THOUSAND PALMS HYDROGEN FUELING STATION

SunLine's hydrogen fueling facilities include solar panels that can power electrolyzers (not shown here) and hydrogen compression into a tube trailer and stationary vessels.

SunLine opened their hydrogen fueling station in April, 2000. This was the first hydrogen station built and operated by a California transit agency. The DOE, SCAQMD, and Clean Air Now supported station development. SunLine, which is the public transit agency in the Coachella Valley area, pioneered the development and use of alternative fuels. They converted their entire bus fleet to CNG in 1994 and they currently have capabilities to dispense CNG, LNG, hydrogen, and Hythane®.

SunLine's hydrogen fueling station is part of a facility designed for hydrogen research, development and education, as well as dispensing. The facility includes multiple components for hydrogen generation, for example, and these components and their capabilities are continually being refined as new technologies become available.

SunLine uses electricity from solar collectors and/or the utility grid to power two electrolyzers. SunLine previously tested a HbT natural gas reformer, and is currently

installing a Hyradix reformer. Hydrogen is compressed and stored in K bottles, a tube trailer, and/or in ground-mounted vessels. A two-hose dispenser provides 3,600-psi hydrogen, and 5,000-psi dispensing capability is being added.

The accompanying simplified schematic diagram illustrates the basic design of SunLine's main hydrogen fueling station that supports fuel cell bus testing. The station's key features and specifications are summarized in the accompanying table. The photographs show various aspects of SunLine's hydrogen station components, which are explained in the captions.
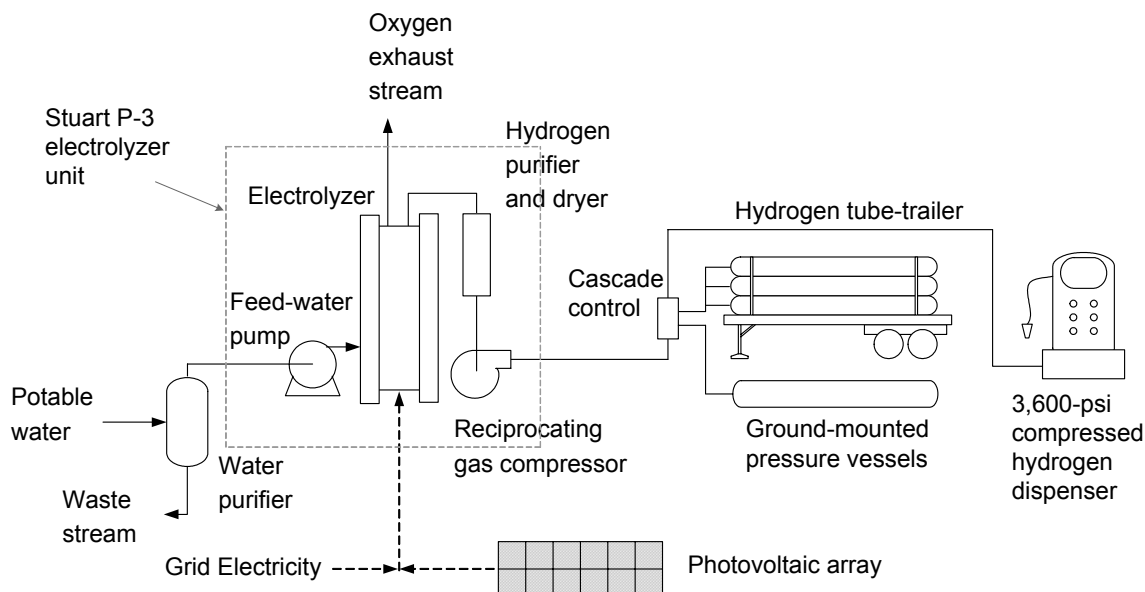
Simplified schematic illustration of SunLine's hydrogen fueling station (not including the Schatz Center equipment)

SunLine's electrolyzers include a relatively small Teledyne Altus 20 unit and a larger-capacity Stuart Energy P-3 unit. The Teledyne electrolyzer requires 7.5 kW of electricity and produces hydrogen at approximately 40 scfh (0.1 kg/hr). It can be powered by SunLine's solar electric system, which includes two photovoltaic arrays: 218 Semens flat panels rated at 16 kW peak output, and 144 Photovoltaic International line-focusing collectors rated at 21 kW peak output. Hydrogen from the Teledyne electrolyzer is dried, compressed (by a PDC-4 diaphragm compressor), and stored in DOT K bottles. Hydrogen produced by this system is usually used to fuel golf carts and the SunBug two-passenger neighborhood vehicle, which are fuel cell powered. These vehicles and the solar-powered Altus electrolyzer are part of the Schatz Hydrogen Generation Center at SunLine.

The Stuart Energy P-3 unit (which is shown in an accompanying photograph) is an integrated electrolyzer, hydrogen dryer and purifier, and compressor. It has a production and compression rating of 1,400 scfh (3.2 kg/hr) and a power requirement of 250 kW. The electrolyzer demonstrates Stuart's MW-CST or multi-stack cell technology. The

Principal hydrogen production unit	Stuart Energy P-3 MW-CST electrolyzer: 1,400 scfh (3.2 kg/hr) production capacity, 250 kW power input, with integral gas dryer/purifier and compressor (below)
Hydrogen dispensing capability	Two-hose FTI dispenser: rated at 3,600-psig for compressed hydrogen at 2 kg per minute, 3,600-psig compressed Hythane® at 2 kg per minute.
Hydrogen drying and purification	Molecular sieve and activated carbon cartridges (integral with Stuart P-3 electrolyzer)
Compressor	Comp-Air Reavell 4-stage reciprocating compressor, intercooled, lubricated, 4,000-psi discharge, 1,400 scfh, 50-hp electric motor driven (integral with Stuart P-3 electrolyzer)
Compressed hydrogen storage	FIBA tube trailer with 16 DOT-type cylinders providing, 96,000 scf (218 kg) total capacity at 3,130 psig, two ASME-coded ground-mounted storage cylinders providing 12,000 scf (28 kg) at 5,500 psig design pressure and 4,000 psig maximum average working pressure, priority-sequenced-cascade connection to dispensers
Compressed hydrogen dispensers	FTI dispenser, Sherex CW 5000 and CW 3600 nozzles, 5,000 and 3,600 psig nozzles, complete with hose break-away connectors.
Example safety features and equipment	Hydrogen leak detection, IR/UV fire detection, various pressure-relief devices and vents, hydrogen production equipment enclosed on SunLine property by chain-link fence with storage and dispensers protected by bollards, storage being 75 feet from buildings.
Area occupied by station	Irregular shape, approximately 12,000 ft^2 (not including setbacks)

Summary of SunLine hydrogen fueling station key features and specifications (not including the Schatz Center equipment)

compressor is a Comp-Air Reavell Model 5000 4-stage reciprocating unit with a rated outlet pressure of 5,000 psi. The gas drying and purification system consists of molecular sieve and activated carbon cartridges configured in series.

SunLine also operated a HbT natural gas reformer for a six-month period in 2001, but this unit is no longer in service. SunLine is currently installing a HyRadix ATR natural gas reformer with a production rating of 3,500 scfh (7.9 kg/hr).

High-pressure hydrogen is stored in a tube trailer and in ground-mounted vessels. The FIBA Technologies tube trailer (which is shown in the first photograph) has 16 DOT-type cylinders, which provide 96,000 scf of storage capacity at 3,130 psi. This trailer has provided temporary fueling capabilities for various hydrogen vehicle projects such as the 2001 Michelin Bibendum Challenge. The two ground-mounted vessels are ASME-type cylinders, which provide 12,500 scf of storage at 4,000 psi. These vessels are integrated by a cascade controller to maximize the storage utilization efficiency.

SunLine is currently reconfiguring the high-pressure hydrogen vessels from a parallel to a series arrangement. The tube trailer will provide lower-pressure buffer storage feeding a diaphragm booster compressor, which will charge the higher-pressure ground-mounted vessels.

The refueling island includes a Hythane® (hydrogen and natural gas mixture) dispenser in addition to a hydrogen dispenser. The Fueling Technologies, Inc. hydrogen dispenser (which is shown in a photograph fueling a Honda FCX fuel cell vehicle) has two hoses, which are equipped with breakaway connectors and Sherex nozzles. The current dispensing capability is 3,600-psi hydrogen. A new two-hose dispenser will provide 5,000-psi hydrogen. The new 5,000-psi hydrogen dispenser will have the CaFCP-type data interface, which transmits real-time vehicle tank temperature and pressure data to the dispenser.

The SunLine station is equipped with various safety features including a chain-link fence enclosing all station components except for the dispenser, which is protected by bollards. The combination IR-UV fire-detection sensors at the dispensing island trigger alarms and a station shutdown sequence. All high-pressure vessels were designed, fabricated, and tested consistent with the ASME Boiler and Pressure Vessel Code or DOT 4L requirements. Station piping conforms to ASME B31.3 specifications. All station mechanical and electrical components conform to applicable codes and standards including NFPA 50A (for compressed hydrogen), the National Electric Code (NEC 70), and the Uniform Fire Code.

Riverside County agencies, including the planning, building, fire, and HAZMAT departments, were involved in permitting SunLine's hydrogen fueling facilities. Permitting was relatively problem-free because of SunLine's previous experience with these agencies in permitting CNG and LNG stations.

SunLine's hydrogen station is used to refuel experimental fuel cell buses (such as those shown in the accompanying photograph), and it is also available for public access. With current hydrogen production capacity exceeding demand, SunLine is planning to use hydrogen for power generation (with fuel cells and a hydrogen-fueled internal combustion engine genset) as well as expanded use of CNG-hydrogen mixtures in its bus fleet. SunLine refers to its continuously evolving CNG, LNG, hydrogen, and Hythane® fueling facilities as a "Clean Fuels Mall."

A Stuart Energy P-3 electrolyzer unit generates, purifies, and compresses hydrogen at a rate of 1,400 scfh.

SunLine's FTI 3,600-psi hydrogen dispenser refueling a Honda FCX fuel cell automobile

SunLine is testing hydrogen-fueled fuel cell buses, methanol-fueled fuel cell buses, and Hythane®- fueled buses with internal combustion engines.

SunLine's "Clean Fuels Mall" includes CNG, LNG, compressed hydrogen, and Hythane® refueling capabilities.

AMERICAN HONDA MOTOR COMPANY

TORRANCE HYDROGEN FUELING STATION

Honda's Hydrogen Fueling Station in Torrance features a solar-powered electrolyzer and aesthetically attractive packaging.

Honda Motor Company is actively engaged in fuel cell vehicle research and development and is a partner in the California Fuel Cell Partnership (CaFCP). Honda has been testing their FCX series of experimental fuel cell vehicles in Japan and the United States. The FCX received ZEV certification from the CARB, and Honda recently initiated a FCX demonstration program in cooperation with the City of Los Angeles. To support their fuel cell vehicle development work in the U.S., Honda has installed a hydrogen fueling station at the American Honda and Honda R&D Americas facility in Torrance, California

The Honda hydrogen fueling station in Torrance, which began operating in the summer of 2001, dispenses compressed hydrogen produced by an electrolysis unit that can be powered by a photovoltaic (PV) solar array. The design and operation of this station addresses multiple objectives. First, Honda needed a hydrogen dispensing facility to

Simplified schematic illustration of the Honda Torrance hydrogen fueling station design

Labels in diagram:

Proton exchange membrane electrolyzer

5,000-psi compressed hydrogen dispensing hose, nozzle, and display

Reverse osmosis and deionizer water purification

Hydrogen dryer

Display and control panel

Compressed hydrogen storage cascade

Enclosure #1

Enclosure #2

Enclosure #3

Water

Electricity from photovoltaic array and/or utility grid

Reciprocationg gas compressor

Low-pressure hydrogen accumulator/buffer tank

Simplified schematic illustration of the Honda Torrance hydrogen fueling station design

support their fuel cell vehicle development and testing activities. Honda also wanted to explore renewable energy technologies associated with hydrogen use as a vehicle fuel. To address this latter objective, Honda engineers carried out most of the station design work. Because of this, and because the station was internally funded by Honda, certain of the station design details and specifications are proprietary to Honda.

The accompanying simplified schematic diagram illustrates the basic design and layout of the Honda hydrogen fueling station in Torrance. The station's key features and specifications are summarized in the accompanying table. The photographs show different views of the station and its components, which are explained in the captions.

Honda gave particular attention to the Torrance station components packaging and overall layout, and this resulted in a very aesthetically pleasing installation. As shown in the diagram and photographs, the station components are all contained in three dark blue rectangular modules, which are underneath an arching canopy:

- The module on the left contains water purifiers, the electrolyzer, and hydrogen dryers.
- The center module houses the gas compressor, dispenser hose, nozzle, and vehicle grounding connector. The user interface panel is mounted on a canopy-support pole near the center module.

- The module on the right (which is the largest) encloses a high-pressure hydrogen storage vessel cascade and a low-pressure hydrogen buffer tank.

The electrolyzer can receive electric power from the PV array, the utility electric grid, or both. Power conditioning equipment rectifies the grid AC to DC and regulates the power from either the grid or PV array to provide the appropriate current and voltage to the electrolyzer.

Hydrogen generation	Proton exchange membrane electrolyzer, approximately 1.8 kg/day maximum output
Feedwater purification	Reverse osmosis and ion exchange
Electric power input	Utility grid, or 8 kW photovoltaic array
Hydrogen dispensing capability	5,000-psi compressed hydrogen, fast-fill or time-fill
Hydrogen compressor	5,000 psi reciprocating compressor
Compressed hydrogen storage	Priority-sequenced high-pressure vessel cascade
Compressed hydrogen dispenser	Honda dispenser, hose break-away coupling, nozzle, vehicle grounding connector and cable
Example station safety features	Hydrogen leak detection, IR fire detection, automatic alarm and shutdown activation, module ventilation, and password-authorized operation. Equipment protected by earth berm, bollards, and canopy.

Summary of Honda hydrogen fueling station key features and specifications

A reverse osmosis unit, followed by a deionizer, purifies the water feeding the electrolyzer in the first module. The electrolyzer itself is a proton exchange membrane (PEM) type. Oxygen is vented. An adsorption process dries hydrogen. The dry hydrogen is then piped to a large-volume low-pressure accumulator tank housed in the third module, which acts as a suction buffer for the compressor in the second (middle) module.

The hydrogen is compressed into high-pressure cylinders housed in the third module. These cylinders are charged and discharged (during fast filling) in a sequenced cascade fashion. Honda has experimented with different cascade strategies. The station can refuel hydrogen vehicles in either of two modes: fast-fill from the cascade, or time-fill directly from the compressor.

The hose is housed and the nozzle is holstered behind a door in the middle module, as shown in the photograph. An electric connector, which provides a grounding connection during refueling, is housed behind the same door. The refueling process is highly automated, and minimal inputs are required from the operator. The operator interface

screen displays information such as the quantity of hydrogen dispensed, the pressures in the cascade tanks, and power from the photovoltaic array. It also serves as a touch screen for operator input instructions. The nozzle itself is the configuration agreed on by the California Fuel Cell Partnership. Refueling is automatically terminated and the display notifies the operator when the vehicle tank pressure reaches 5,000 psi.

A central electronic control unit (ECU) controls the Honda station. The station has various safety features such as hydrogen leak detectors in each module. The module cabinets are designed to have natural ventilation when the station is not in use and forced ventilation when it is operating. An infrared (IR) camera calibrated for fire detection camera monitors the overall station. Multi-color lights signal various levels of station problems. A yellow light is illuminated if the ECU detects an equipment problem. A blue light flashes and an alarm sounds if a hydrogen leak is detected. A red light flashes, a loud siren is activated, and the fire department is notified if the IR camera detects a flame.

Honda and its installation contractors worked with the City of Torrance to secure various permits for the station. Communications were initiated early with the Torrance Planning, Building, and Fire Departments. This helped the permitting process to proceed smoothly, but the time frame was lengthened by the lack of codes and standards specific to hydrogen fueling stations and certain components from Japan that required third-party certification. Codes and Standards referred to during the permitting process include: NFPA 50A, 30, 88, 70, 496, 497A; the ASME Boiler and Pressure Vessel Code (Section VIII and pertaining to relief devices); and California Fire Code Article 52 (pertaining to automotive fuel dispensing stations). Honda and the Torrance Fire Department conducted a facility HAZOP analysis. They also jointly developed an emergency response plan, which defines specific actions for various levels of emergencies.
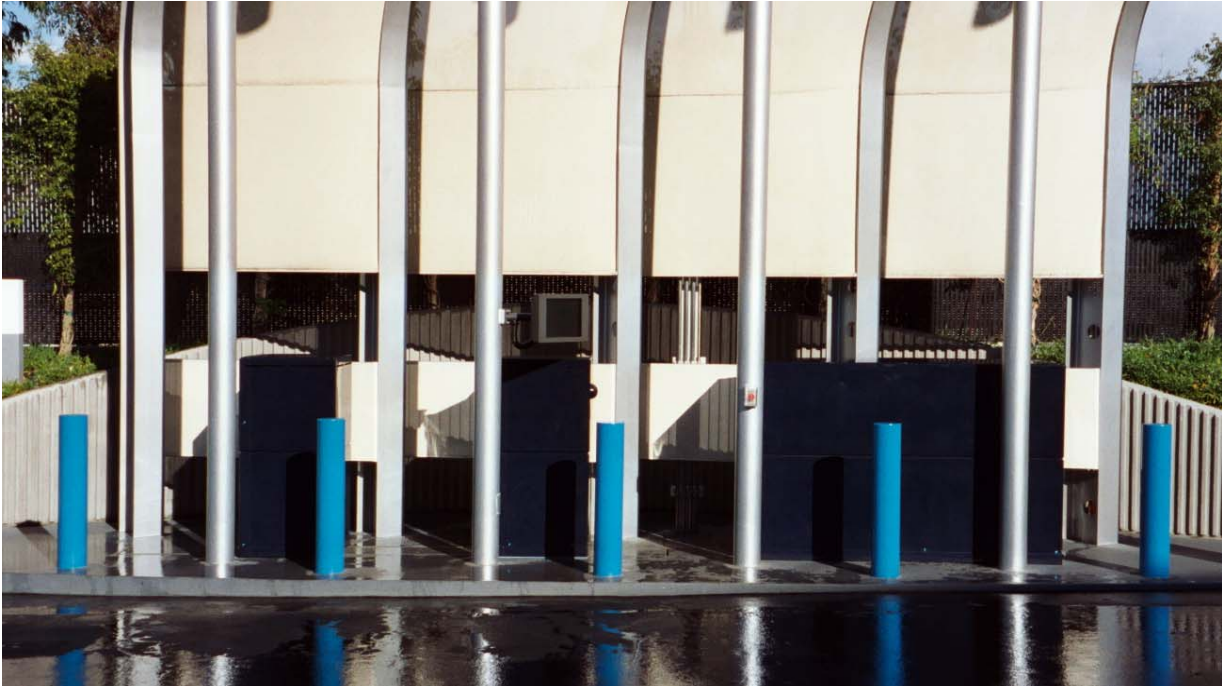
The electrolyzer and hydrogen compression, storage, and dispensing equipment are enclosed in three modules.

The refueling hose and nozzle, and the vehicle grounding connector and cable, are housed in the center module.

The dispensing nozzle and grounding connector attach to corresponding vehicle receptacles.

The Torrance station supports Honda FCX fuel cell vehicle testing.

CALIFORNIA FUEL CELL PARTNERSHIP

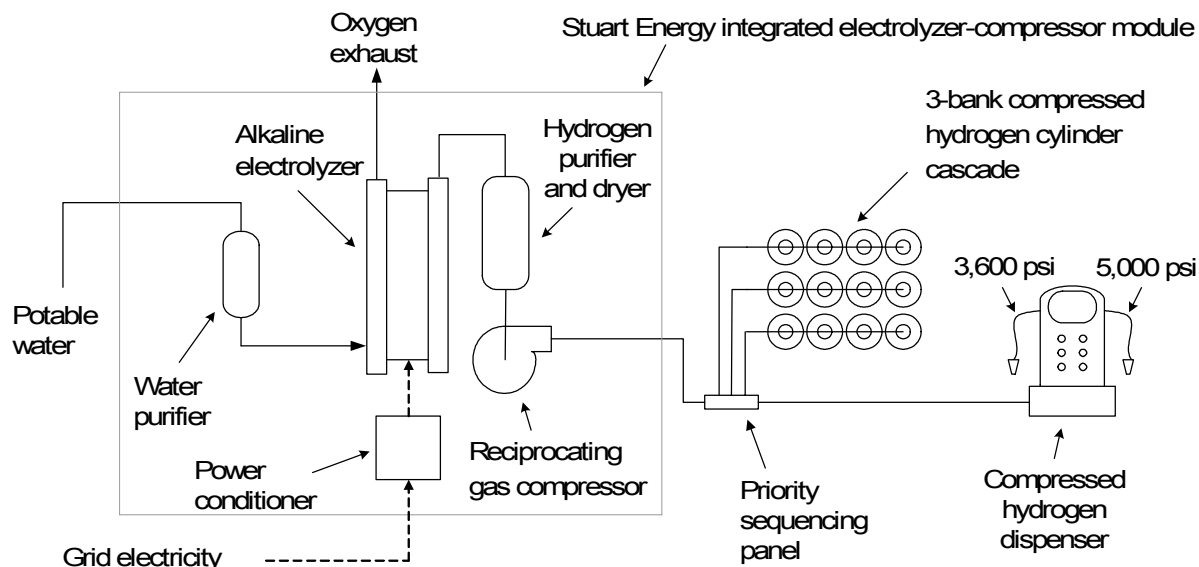# RICHMOND SATELLITE HYDROGEN FUELING STATION

The first California Fuel Cell Partnership satellite station is located on AC Transit property in Richmond.

Alameda Contra Costa Transit District (AC Transit) and Stuart Energy Systems Corporation collaborated to install a compressed hydrogen fueling station at an AC Transit property in Richmond, California. This station, which opened on October 30, 2002, is the first California Fuel Cell Partnership (CaFCP) "satellite" hydrogen fueling station. It will enable fuel cell vehicles traveling from the CaFCP headquarters in West Sacramento to refuel in the San Francisco Bay Area. The AC Transit and Stuart Energy collaboration to install this station was part of their in-kind contribution toward CaFCP membership.

The Richmond station utilizes an electric-grid-powered water electrolyzer to produce hydrogen. The Stuart Energy alkaline-type electrolyzer produces up to 450 scfh (approximately 12 Mm^{3}h or 1.1 kg/hr), and the integrated unit includes a hydrogen compressor and other auxiliary equipment. The purified and compressed hydrogen is stored in a three-bank pressure vessel cascade with a total capacity of approximately 47 kg. The dispenser has two hoses, which provide 3,600-psi and 5,000-psi refueling

capabilities. Stuart Energy refers to the Richmond station as a Hydrogen Energy Station, HES-12f.

The accompanying simplified schematic illustrates the basic design of the Richmond station. The station's key features and specifications are summarized in the accompanying table. The photographs show different views of the station and its components, which are explained in the captions.

Simplified schematic illustration of the Richmond hydrogen fueling station design

The Richmond hydrogen fueling station was designed and built by Stuart Energy in cooperation with AC Transit. The principal components of the station are the electrolyzer and compressor module, the compressed hydrogen storage vessel cascade, and the two-hose hydrogen dispenser. The Stuart Energy electrolyzer and compressor module is an integrated unit, which includes power conditioning equipment, water pretreatment equipment, the electrolyzer, gas demister and purification systems, the compressor, a control system, and safety equipment. This equipment is packaged in a 13 ft long by 4.6 ft wide by 8.5 ft high enclosure, which is mounted on a concrete pad near the back of the station.

The station receives 480-volt, 3-phase electric service, which powers the electrolyzer, compressor, and auxiliary equipment. The power for the electrolyzer is transformed and rectified. Total AC power consumption is stated by Stuart Energy to be approximately 15 kW per 100 scf of H_2 generated. City water is purified by a demineralizer system. Water consumption is approximately 0.75 gallons per 100 scf of H_2 generated. The electrolyzer itself is an alkaline-type, which utilizes Stuart Energy Double Electrode Plate (DEP®) electrolytic cell stacks. Oxygen and hydrogen from the electrolyzer flow to a gas seal / demister, and oxygen is vented to the atmosphere. The hydrogen is purified

in integrated dual pressure-swing absorption (PSA) dryers, coalescing and carbon adsorption filters, and a de-oxifier system.

The hydrogen compressor is a 4-stage, air-cooled, reciprocating type driven by an electric motor. A standby compressor is included in addition to the duty compressor. Additional equipment integrated into the Stuart Energy module includes a cooling-water system, condensate collection system, instrumentation and controls, hydrogen leak detectors, and pressure relief valves.

Compressed hydrogen is stored in 12 pressure vessels configured as a 3-bank cascade with 4 vessels in each bank. The vessels are Type III (composite over wrapped aluminum liners) manufactured by Dynetek. Each vessel has a water volume of 150 liters, and this provides a total of approximately 47 kg of hydrogen storage at 5,700 psi. The vessels are mounted in a rack, which is installed on a concrete pad, as shown in the photograph. Three pressure-relief valves (which feed into a common vent stack) are provided for the three banks of vessels.

Hydrogen production	Alkaline-type electrolyzer. Up to 450 scfh (approximately 1.1 kg/hr). Uses Stuart Energy Double Electrode Plate (DEP$^®$) electrolytic cell stacks.
Electrolyzer auxiliary equipment	Water purification (demineralizer cartridges), electric power conditioning, cooling water system, gas seal and demister, gas dryer and purifier (PSA, de-oxifier, and filters) and safety equipment (see below).
Hydrogen compressor	Four-stage reciprocating compressor, air-cooled, oil-lubricated, electric motor drive. Two compressors: duty and standby.
Integrated unit	Stuart Energy integrated unit includes feedwater processing, power conditioning, electrolyzer, gas demister and purification, compression, cooling system, instrumentation and controls, and safety systems (see below). Dimensions = 13 ft long x 4.6 ft wide x 8.5 ft high. Weight (in operation) = 12,000 lb.
Electric power required	Approximately 15 kWh per 100 scf of hydrogen (for integrated unit including electrolyzer, compressor, and auxiliary equipment). 480 VAC, 3 phase.
Compressed hydrogen storage	12 Dynetek pressure vessels, Type III (composite overwrapped aluminum liner), each 150-liter (water volume), provide a total of approximately 47 kg of storage at 5,700 psi.
Compressed hydrogen dispenser	FTI dispenser with 3,600-psi and 5,000-psi hoses and nozzles. Includes card-lock system, data display and control panel, and Sherex nozzles. Capable of providing CaFCP Type 1, 2, and 3 filling.
Example safety equipment and features	Hydrogen leak-detection, IR fire-detection, various PRVs and fusible links, chain-link fence and barricade protection, hose breakaway connections, card-lock restricted access.

Summary of Richmond hydrogen fueling station key features and specifications

Fueling Technology Inc. (FTI) manufactures the dispenser. It has two hoses and nozzles: one for dispensing hydrogen at 3,600 psi and one for dispensing hydrogen at 5,000 psi. The dispenser includes the priority-sequencing system for controlling flow from the compressor to the pressure vessel cascade and from the cascade to the dispenser. The dispenser also includes a card reader as well as controls and displays (vehicle tank pressure, quantity of hydrogen dispersed, cost of hydrogen dispersed). The dispenser is capable of supporting the Type 1, 2, and 3 filling protocols developed by the CaFCP. Type 1 filling denotes the situation where a communications cable is connected to the vehicle so that the dispenser receives fuel tank volume, pressure, and temperature signals in order to automatically correct for heat-of-compression effects. Type 2 (5,000 psi) and Type 3 (3,600 psi) fills are without data transmission, and these refuel at a purposely reduced flow rate.

The Richmond station includes a variety of safety features, most of which are standard aspects of the station components. For example, the station has hydrogen leak detectors, various pressure-relief valves, and fault-sensing controls. The dispenser safety features include card-reader access control, breakaway hose couplings, an easily accessible emergency shutdown device (ESD), and various valves to control excess flow, overpressures, etc. The Sherex nozzles are configured so that it is impossible to refuel a 3,600-psi vehicle with the 5,000-psi hose. For fire protection, an IR detector monitors the hydrogen storage and dispensing areas, and the pressure vessel cascade is fitted with fusible links and plugs. The overall station is enclosed in a chain-link fence and protected by barricades, which were requested by AC Transit site safety personnel.

Permitting of the Richmond station involved coordination with the City of Richmond and Contra Costa County Planning, Building, and Fire departments. An environmental review was considered, but the City of Richmond granted a negative declaration (i.e., no impact), and this saved considerable time. The permitting process, nevertheless, required many months because most of the steps had to be carried out in a serial fashion. AC Transit and Stuart Energy conducted some "outreach" activities with neighborhood groups as well as permitting agencies in order to familiarize them with hydrogen vehicle and fueling station technology including appropriate safety information. The primary standards applied by the Fire Marshall were NFPA 52 (CNG Vehicle Fuel Systems) and NFPA 50A (Gaseous Hydrogen at Consumer Sites). The facility was granted a conditional use permit, which must be renewed periodically.

After the Richmond station was installed, it was determined that the hydrogen storage pressure vessels must be designed, constructed, tested, and marked in accordance with the ASME Boiler and Pressure Vessel Code in order to comply with California Code of Regulations Title 13 (Division of Occupational Safety and Health, DOSH) requirements. The Dynetek Type III pressure vessels comply with codes and standards (e.g., FMVSS 304, NFPA52, NGV2) other than the ASME code, and so Stuart Energy and AC Transit have applied to DOSH for a variance in this regard.

Hydrogen is produced by a Stuart Energy module, which includes the electrolyzer, compressors, and auxiliary equipment.

High-pressure hydrogen is stored in 12 Dynetek Type III vessels arranged as a 3-bank cascade.

The FTI hydrogen dispenser has two hoses and nozzles for 3,600-psi and 5,000-psi refueling.

The compact Richmond station is enclosed in a chain-link fence and protected by barricades.

BMW OF NORTH AMERICA
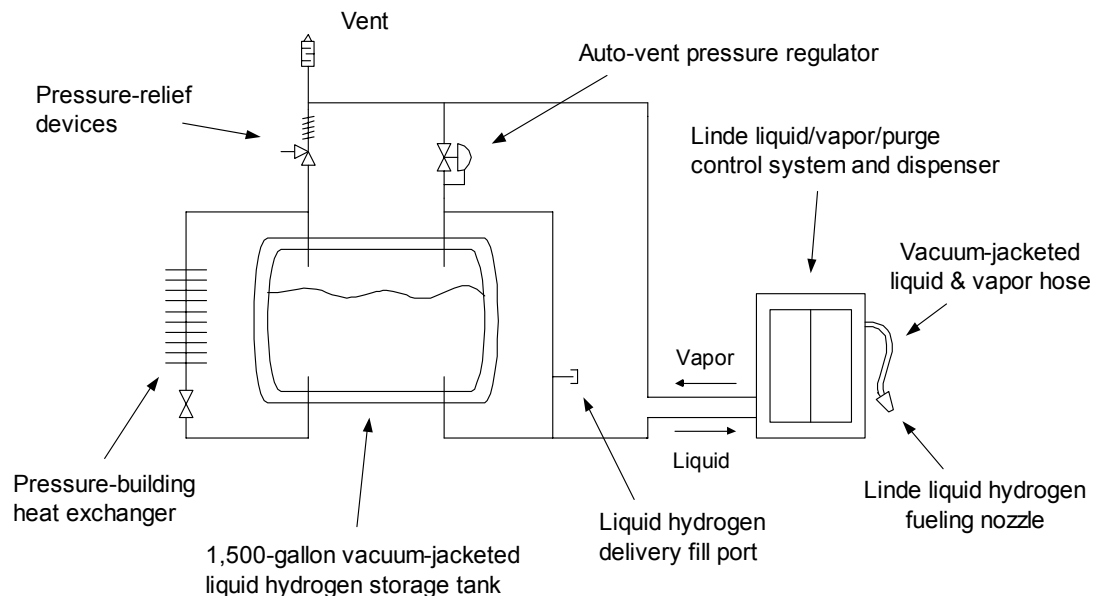
OXNARD HYDROGEN FUELING STATION

BMW's station in Oxnard is a relatively simple and compact design for dispensing liquid hydrogen.

BMW has pioneered the development of hydrogen use as an automotive fuel. Since the 1970's, BMW's research and testing has focused primarily on hydrogen-fueled internal combustion engines and the liquid hydrogen storage mode. BMW conducted their 2001 and 2002 Clean Energy World Tour in order to publicize their hydrogen vehicle technologies. These demonstrations, which included stops in Sacramento and other California cities, continued on to other parts of North America as well as Europe and Asia. The tour featured a fleet of liquid-hydrogen-fueled 750 hL sedans with 12-cylinder engines and fuel cell auxiliary power units.

In order to support the Clean Energy World Tour, as well as their U.S.-based hydrogen vehicle development work, BMW installed a liquid hydrogen fueling station at their Emissions Control and Test Center in Oxnard. This station was designed and installed in only three months in order to accommodate the tour schedule. The Oxnard station is relatively simple and compact. It receives, stores, and dispenses only liquid hydrogen. The station was planned, designed, and installed by a team that included BMW, Air Products and Chemicals (APCI), Linde, BP, K. A. Serv (architects and engineers), C. D. Lyon (construction contractor), the City of Oxnard, and CARB.

The accompanying simplified schematic diagram illustrates the basic design of the BMW liquid hydrogen fueling station in Oxnard. The station's key features and specifications are summarized in the accompanying table. The photographs show different views of the station and its components, which are explained in the captions.

Simplified schematic of the BMW liquid hydrogen fueling station in Oxnard

The relatively simple and compact design of the BMW Oxnard station is facilitated by several factors: It stores and dispenses only liquid hydrogen. This enables use of a pressure-transfer system, and so no pump or compressor is required. A packaged Linde system for liquid hydrogen dispensing is employed. The station is located within BMW North America's Engineering and Emissions Test Center facility. It is installed in the corner area of a fenced vehicle staging area as shown in the photographs. A sliding gate opens to enable fueling of hydrogen vehicles parked on a concrete pad outside of the staging area.

The station stores liquid in a 1,500-gallon gross capacity vacuum-jacketed cryogenic tank. The liquid hydrogen is maintained near 45 psi (-413°F) by a pressure-build and auto-vent system. When the tank pressure drops below approximately 40 psi (e.g., after receiving a liquid hydrogen tank truck delivery), the regulator valve opens so that liquid hydrogen is vaporized in the heat exchanger. The vapor is routed to the storage tank ullage where it increases the pressure by creating a "false head" and eventually increases the stored hydrogen saturation pressure and temperature. When the tank pressure exceeds approximately 50 psi, vapor is vented to the atmosphere to maintain the pressure at that level. At 45 psi, the tank capacity is approximately 350 kg of liquid hydrogen.

Hydrogen delivery and storage	Liquid hydrogen, delivered by cryogenic tank truck
Hydrogen dispensing capability	One liquid hydrogen dispenser, dispensing rate depends on vehicle fuel tank conditions
Liquid hydrogen storage tank	APCI 1,500-gallon gross capacity vacuum-jacketed vessel, ASME-coded, 150-psi MAWP, approximately 3% per day normal evaporation rate
Storage tank pressure management	Pressure-building ambient-air heat exchanger, auto-vent pressure regulator
Dispensing liquid hydrogen transfer	Pressure transfer; no pump, no compressor
Dispenser liquid and vapor management controls	Linde system; automatically controls cool-down, helium purging, vapor return from vehicle tank, and liquid supply to vehicle tank. System utilizes nitrogen-actuated pneumatic controls.
Dispenser hose and nozzle	Linde hose and nozzle; vacuum-jacketed hose with central liquid supply and vapor return through annulus. Nozzle employs latching coupling, automatic pressure-tight seal check, and filling tube that extends into vehicle receptacle.
Example safety features and equipment	Hydrogen leak detectors and fire monitor. Fire suppression nozzle that can be connected to fire hydrant. Station equipment is enclosed within a chin-link fence and protected by bollards. 50-ft separation from adjacent buildings. Equipped with various pressure-relief devices and elevated vent. Linde dispenser system includes safeguards such as automatic coupling leak check. Remote emergency stop panel.
Area occupied by stadium	Approximately 800 ft^2 (not including setbacks)

Summary of BMW Oxnard hydrogen fueling station key features and specifications

The 45-psi storage tank pressure is adequate to transfer liquid through the dispenser and into the vehicle tank, i.e., without a pump or compressor. The vehicle fueling operation is controlled by a packaged Linde liquid hydrogen fueling system. This system is the stainless steel enclosure shown in the photographs. Linde designed this system as a mobile hydrogen fueling station, but it is a stationary installation in this application.

The automatic control system commands nitrogen-actuated pneumatic valves that control the liquid hydrogen, hydrogen vapor, and helium purge flows. As shown in the photograph, the Linde nozzle is holstered behind an access door in the cabinet. The hose flows liquid hydrogen through its center, returns vapor through an annular passage, and is vacuum jacketed.

To refuel a hydrogen vehicle, the station gate and dispenser cabinet door are both opened, the nozzle is connected to the vehicle receptacle, and the following sequence is initiated:

- The helium purge gas pressure is automatically monitored to ensure that a leak-tight connection has been made, and a "connect" signal is displayed
- The operator opens the coupling valve and presses the "fueling on" button
- The nozzle inner filling tube extends into the vehicle receptacle and starts flowing liquid hydrogen into the vehicle fuel tank
- Hydrogen vapor from the cool-down and vehicle tank ullage is routed back to the station vent
- Liquid hydrogen flow is terminated by the operator or when the control system senses that the vehicle tank is full
- When a "disconnect" signal is displayed, the operator closes the coupling valve and removes the nozzle from the vehicle receptacle

K.A. Serv, with support from BMW, APCI, and other project partners, managed the BMW hydrogen fueling station permitting. The City of Oxnard Planning, Building, and Fire Departments were involved in facility permits, reviews, and inspections. K.A. Serv was proactive in providing these agencies with copies of what it judged to be applicable codes and standards including NFPA 50B. The Oxnard Planning Department issued a Discretionary Permit, and the Building Department issued a Construction Permit. Specific safety features recommended by the Oxnard Fire Department and incorporated in the installed station include a fire suppression system, which can be connected to a fire hydrant (the nozzle is at the end of the red pipe in the photographs), and a concrete pad under the vehicle being fueled (which was also recommended by APCI).

This view from inside the compound shows the Linde cabinet, liquid hydrogen tank and vent stacks, compressed helium/ nitrogen/hydrogen bottles, and fire-suppression nozzle.

The pressure-building ambient heat exchanger is on the side of the 1,500-gallon liquid hydrogen storage tank.

Liquid hydrogen tank trucks refill the storage tank through this fill connection.

The refueling nozzle and hose are holstered behind an access door in the Linde control and dispenser cabinet.

The Linde refueling nozzle latches to the vehicles receptacle and enables automated purge, leak-check, vapor-return, and liquid hydrogen dispensing.